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MATERIALS *of* ENGINEERING CONSTRUCTION

By

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PREFACE

No problem presents itself more frequently to the engineer for careful solution than the selection of materials for tools, machines, structures, and other engineering works. Necessity compels the engineer to acquire a working knowledge of all the engineering materials, and to keep in constant contact with their progressive improvement and development.

This book has been planned and written as a text for the student of engineering, to enable him to obtain a close acquaintance with the characteristics and properties of the more common and most widely used materials of engineering. The principle followed in the selection of the information, and its manner of presentation, is that of lasting usefulness, both as to pertinent facts and those deep impressions that aid in forming engineering judgment. No attempt has been made to produce a manual of engineering materials, and for that reason the treatment is rather different from that of most college texts on its subject.

To conserve both the time and energy of the student and reader, explanations and descriptions have been made as brief and direct as possible. There is little or no necessity for analysis of tabular data, nor lengthy search for the significance of diagrams and charts. Reproductions of photographs have been used freely in order to visualize materials and their characteristics.

Existing text and reference books have been consulted as to points of view, available information, and effectiveness of treatment. In addition, government reports, publications of testing laboratories and institutes, and the current proceedings of technical societies have been explored. From these latter sources a wealth of data has been taken.

The characteristics of comprehensive treatment, concise statement, consideration of current developments, generous illustrations, and practical usefulness, will appeal to engineers in practice and industry, particularly to those who wish to extend the horizon of their working knowledge, and to explore somewhat beyond the boundaries of commonplace experience.

Acknowledgment is due to many individuals and organizations for the cooperation and help which has made this book possible. Special appreciation is due to the Forest Service of the United States; the Portland Cement Association; Wrought Iron Research Association; Enrique Touceda, consulting engineer for the Malleable Iron Association; The Aluminum Company of America and J. O. Chesley in particular; the American Steel & Wire Company and E. E. Legge; Professor H. F. Moore of the University of Illinois; Dr. F. F. Lucas of the Bell Telephone Laboratories; Dr. K. F. Mather of the Department of Geology, Harvard University; and Carl Johnson of the Worcester Polytechnic Institute.

FRANCIS W. ROYS.

Worcester, Massachusetts,
March 15, 1930.

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MATERIALS OF
ENGINEERING CONSTRUCTION

CHAPTER 1

MECHANICS OF MATERIALS: DEFINITIONS AND CONCEPTS

To aid the student and reader in readily understanding the reasons for various aspects of the consideration of materials of engineering, as presented in this book, a brief discussion is given in the following paragraphs, of certain definitions and concepts that are fundamental to such a consideration.

Deformation and Stress.—When solid materials are acted upon by external forces they tend to become distorted according to the nature of the forces applied. In general, the distortion is called *strain,* while the internal forces set up in opposition constitute *stress.*

Kinds of Stress.—Stress may be divided, primarily, into two classes—*direct stress* and *shearing stress.* Direct stress is the internal resisting force, normal to the plane of reference, within the material. Shearing stress is the internal resisting force, parallel to the plane of reference, within the material.

Direct stress will tend either to separate or press together two adjacent sections and is therefore expressed as either *tension* or *compression,* and the strain is, primarily, in a direction normal to the plane of reference.

Shearing stress evidently will tend to slide one plane relative to a plane adjacent, and the strain will obviously produce an angular distortion.

A structural element designed to resist the tendency of the structure to pull apart, or separate, is called a *tension member.* Upon such a member the external forces are directed away from each other, are in the same straight line, and are so distributed that the line of action of the resultant coincides with the center of gravity of the cross-section. If the line of action does not coincide with the center of gravity of the cross-section, the member is said to be *eccentrically loaded.*

A structural member designed to resist the tendency of the structure to close, or push together, is called a *compression member.* So far as external characteristics are concerned, the only difference between a *compression member* and a *tension member* is in the direction of the external forces.

Structural members having more than two points of application of force, forces being not in the same straight line, are subjected to bending and are called *flexure members.* When the members are sufficiently long, and the transverse loading components are sufficiently large, in comparison to the longitudinal components, they are called *beams,* and *beam action* is said to occur. The stresses set up under these conditions are collectively known as *flexure stresses* or bending stresses. Any treatise on the mechanics of materials will analyze the distribution and magnitude of such stresses under various conditions of loading and for various structural shapes.

The resistance to angular distortion of a structure may be by the use of properly placed tension and compression members, but such a resistance is often afforded by a single member, as, for instance, by a shaft. In such a member there exists a tendency to produce rotational, instead of translational, slipping between adjacent cross-sectional planes and under such a condition *torsional shear is said to exist* and the stresses set up are known as *torsional stresses.*

Combined stress is understood to denote the stress distribution existing when various combinations of the conditions described above occur, i. e., combined tension or compression and bending; combined tension or compression and torsion; combined torsion and bending; and tension or compression combined with both torsion and bending.

Elastic and Plastic Bodies.—When a body is deformed under the action of externally applied forces it may or may not return to its original shape when the forces cease to act. If the body returns to its original shape upon the removal of the forces, it is said to be a *perfectly elastic body.* On the other hand, if it does not return at all, it is said to be *perfectly plastic.* Very few, if any, materials are absolutely in the class of either of these groups, but many approach it so closely that for all practical purposes they can be included in either one group or the other, for at least a part of the stress range to which they may be subjected. However, there is a tremendous assortment of materials, whose properties are between these two extremes, which are partially elastic and partially plastic, the relative amounts of elasticity and plasticity depending upon the material and various other conditions. Some materials are almost at one extreme under some conditions and almost at the other extreme under other conditions.

Modulus of Elasticity: Modulus of Rigidity.—When an elastic body is subjected to a direct stress, a lengthening or a shortening in a direction parallel to the direction of the direct stress occurs. The ratio of the unit stress to the unit strain is known as the *Modulus of Elasticity* and is generally designated by the letter E. If the total stress on a section be represented by the letter P, the area by A, and the change of the length in a length by l, by e, then

$$E = \frac{P}{A}\Big/\frac{e}{l} = \frac{Pl}{Ae}.$$

When an elastic material is subjected to shearing stress, a displacement of one plane in a direction parallel to another takes place. The ratio of the unit shearing stress to the displacement per unit length is the *Modulus of Rigidity* or the *Shear Modulus of Elasticity,* generally designated by the symbol E_s. If the total shearing stress on a section be represented by Q; the area by A; and the lateral displacement in a length by l, by e_s, then $E_s = \frac{Q}{A} / \frac{e_s}{l}$ but since e_s is measured in a direction normal to l, and since the displacement under working load in rigid bodies is relatively very small, $\frac{e_s}{l}$ becomes the measure of the angle of displacement, or of the *angle of shear* ϕ, so that $E_s = Q/A\phi$.

It should be noted that the volume of materials under stress does not remain constant and the mathematical analysis and discussion of this phenomenon of volumetric change under stress will be found in any good text on the mechanics of materials.

Materials Under Tensile Stress.—Many of the materials of engineering are, for all practical purposes, perfectly elastic through at least a part of the range of their ability to carry load. In other words, there will be no measurable permanent set when load is removed, and in many cases stress will be perfectly proportional to strain. However, at some more or less elevated stress, a phenomenon known as elastic breakdown occurs, and stress no longer remains proportional to strain; permanent deformation begins, and the *elastic limit* is said to have been reached. In some materials, at a stress value a little above the elastic limit (E.L.), there is a considerable plastic deformation without any increase (and often with a slight decrease) of stress. This is called the *yield point* (Y. P.).

Further increase in stress results in much plastic strain and some elastic strain, and a gradual decrease in cross-section, until a maximum load is reached. This maximum load divided by the original area of section is known as the *ultimate stress*. After the ultimate stress is reached, the material either breaks, or, if it is sufficiently plastic, a local, rapid decrease of diameter known as "necking" or "necking in" occurs, and finally the material fractures at a somewhat reduced load. Figure 1 illustrates the curves which would be obtained in recording the results of tension tests of the type of material referred to just above.

The ratio of the reduction in area of the cross-section at the fracture to the original cross-section, multiplied by 100 is

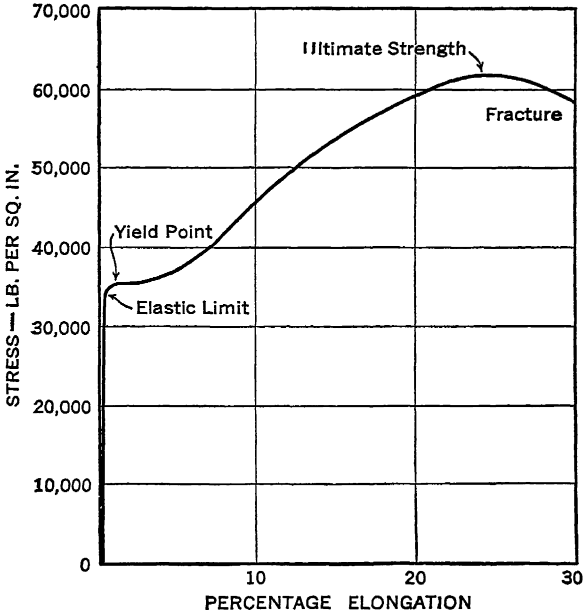


Figure 1. Stress-Strain Curve—Tension Test of Structural Steel, Elastic Over Part of Range, and Quite Plastic Over the Rest of Range

called the *percentage reduction in area.* A high percentage reduction of area is generally considered to indicate an ability to withstand cold bending without cracking.

If gauge marks indicating units of length are made before tensile load is applied and the percentage of increase of length as compared to the original length is noted, the result is known as the *percentage of elongation.* This elongation should always be measured so as to include the fractured section and must always be referred to as relative to some definite original length and diameter. The reason for this becomes apparent at once on examination of Figure 2 which shows the effect of the ratio of length to diameter upon the percentage of elongation. Ratios of l/d in samples used for commercial tension tests generally range from about 2.5 to 20. The most common combinations for round bars are as follows:

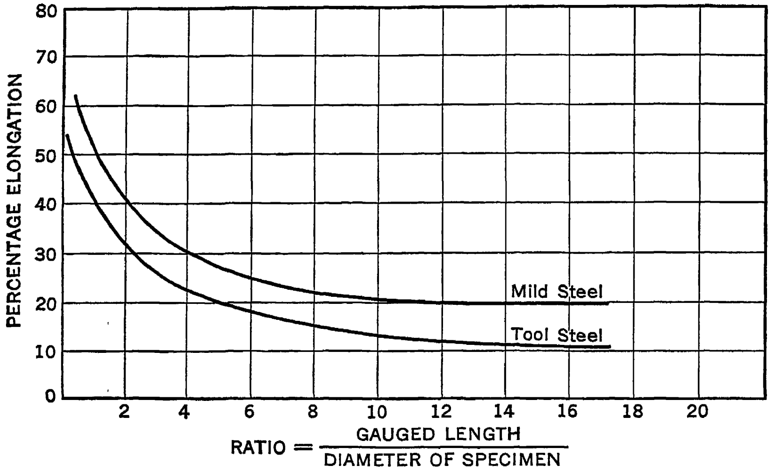


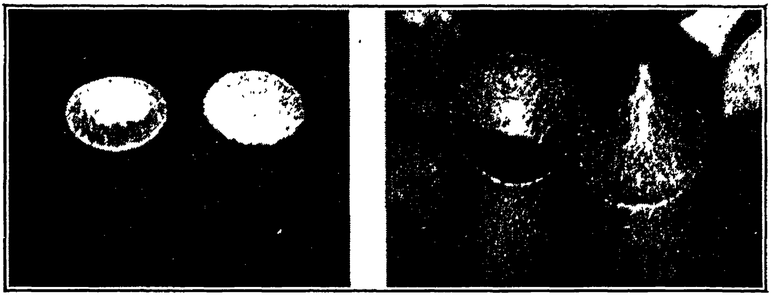
Figure 2. Effect of Ratio of Length to Diameter upon the Percentage of Elongation of Steel

2″	gauge	length	0.798″	diameter	0.5	sq.	in.	area
2″	"	"	.505″*	"	.2	"	"	"
8″	"	"	.798″	"	.5	"	"	"
8″	"	"	.505″	"	.2	"	"	"
10″	"	"	.798″	"	.5	"	"	"
10″	"	"	.505″	"	.2	"	"	"

* Standard.

Nature of Failure of Materials Under Tensile Stress.—

Ductile Materials. When ductile materials are stressed to elastic breakdown, slip or shear lines will appear at an angle of approximately 45° with the direction of the principal stress. This shearing adjustment proceeds through the length of the sample (if of uniform section and homogeneous) and reaches a maximum at the location of the fracture. Failure starts by shear in the outer fibres and progresses toward the center, on a conical, 45° surface. Generally the normal stress at the section increases so much faster than the shear can progress that the completion of the fracture is on approximate right section, and is a pure tension fracture. This combination, shear and tension fracture, results in the characteristic "cup and cone" fracture of ductile materials.



Ordinary "cup and cone" fracture: cold-rolled steel.

Extraordinary "cup and cone" fracture: manganese bronze.

Figure 3. Examples of "Cup and Cone" Fractures

On very rare occasions the shear fracture is complete and a perfect pointed cone results. The accompanying photographs (Figure 3) show both the ordinary and the extraordinary fractures. Brittle material in tension, or material with relatively high shear strength fails without any of the "cupping" phenomenon and generally with little "necking."

Materials Under Crushing Stress.—Up to the elastic limit materials under crushing stress display characteristics entirely similar to those which they display in tension, but beyond the elastic limit, plastic materials flow and increase in diameter, taking more and more load as the area increases. Brittle or non-plastic materials sometimes burst or shatter, but generally tend to fail by shear on planes inclined more than 45° to the principal stress plane. The exact angle of failure depends upon the friction coefficient on the planes of failure. Figure 4, reproduced from photographs of compression failure of soft steel, concrete, and cast iron, shows interesting examples of the conditions described.

Crushing of compression members whose length is considerable as compared to the least dimension of the cross-section involves flexure as well as compression, and buckling takes place. Such conditions are generally referred to as "column action." The theory of column resistance is completely discussed in any good text on the mechanics of materials.

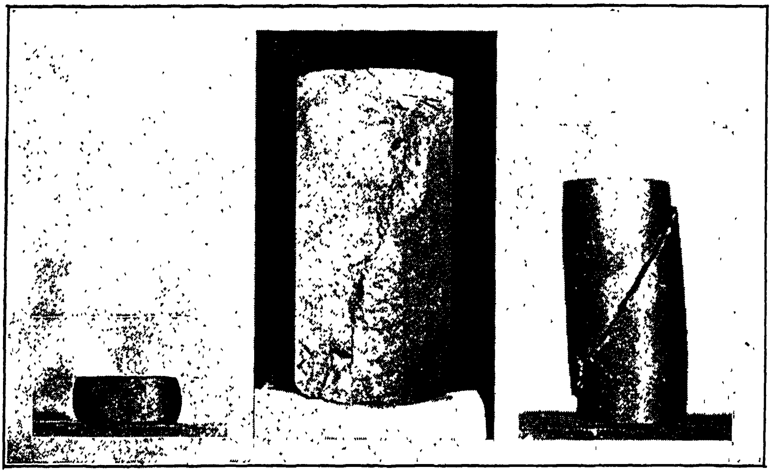

SOFT STEEL CONCRETE CAST IRON
Compressed to 1/3 original length.

Figure 4. Compression Failures

Materials Under Shearing Stress.—In the discussion of action of shearing stress, reference to stress distribution on a unit cube is very helpful. If shearing stresses, A, act on the opposite ends of a unit cube (see Figure 5), it will be quite evident that with them alone, equilibrium would not exist and rotation would occur. The couple which resists this tendency to rotation of the cube is induced by the reaction of two more shearing forces, B, automatically set up in a direction normal to the direction of the forces, A.

It will therefore be seen that parallel to m-m or n-n, pure shear will exist, while parallel to the diagonal g-g, there will be no shear. The same condition will exist relative to the plane of the other diagonal. Those oblique planes of zero shearing stress are the "principal planes," and it will be seen that the stress normal to the principal plane g-g will be tension, while normal to the other principal plane the stress would be compression.

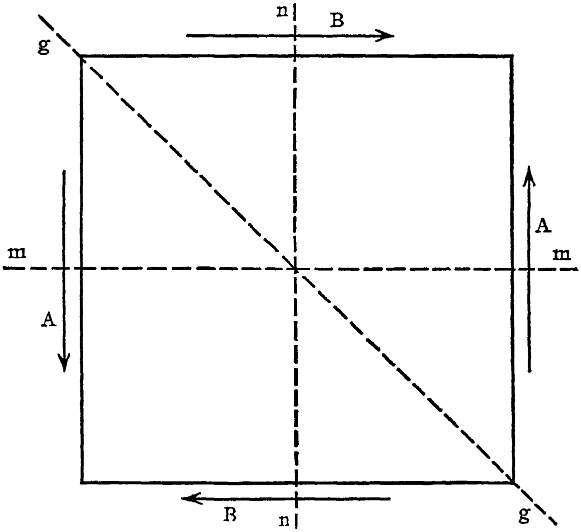
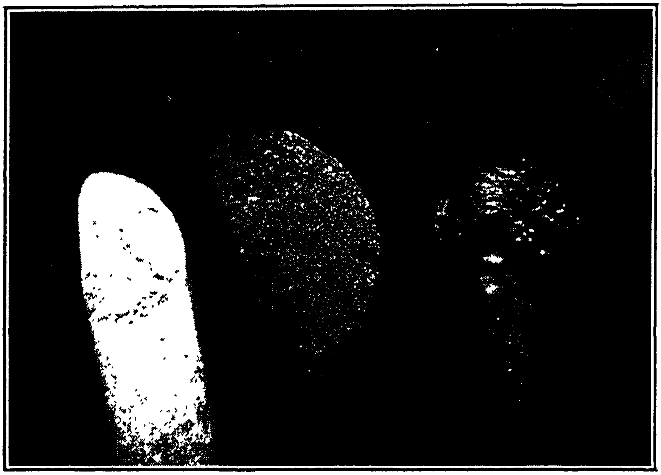


Figure 5. Diagram of Shearing Stresses

Ductile materials naturally begin to fail or flow by a progressive shearing action until the distortion has become so great that no further flow is possible without fracture, and after the limit of plastic flow is reached ductile materials generally fail by shear nearly parallel to the direction of the shearing force.

Brittle materials tend to flow but they cannot stand plastic deformation. Furthermore, such materials are generally stronger in shear than in tension, and since the maximum tension is developed normal to one of the principal planes, the fracture of brittle materials generally occurs as a tension failure along one of the principal planes. Figure 6 shows the typical failures of three round bars of different material all fractured by torsional shear; (c) is the typical failure for a ductile material, while (a) and (b) are typical for brittle materials.



(a) CHALK (b) CAST IRON (c) STEEL

Figure 6. Typical Torsional Failures

Combined Stress.—Failure under combined stress results from a combination of the conditions described above. The position of the principal planes and the maximum shear planes may be calculated readily and full discussion will be found in texts on the mechanics of materials.

Failure under Flexure or Bending.—Failure under bending action may occur as: (a) compression of the outer fibres at the section of maximum bending moment; (b) tension of the outer fibres at the point of maximum bending moment; (c) longitudinal shear where the vertical shear is heavy; or (d) diagonal tension or compression where the shear is heavy.

For the purpose of illustration, consider a simple beam with a central load distributed over a short section (see Figure 7).

The beam theory in the mechanics of materials will demonstrate that the maximum compression parallel to the length of the beam will occur at C; maximum tension at T; and the greatest vertical and longitudinal shear at S. It will also demonstrate that the direction of the principal stresses will be as indicated by the dotted lines shown.

Further than this the beam theory will demonstrate that if the beam is long and slender, C and T will be relatively large and S relatively small, while if the beam is short and chunky, S will be large and C and T relatively smaller.

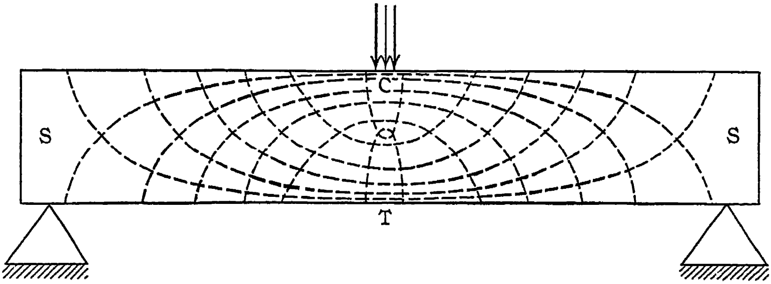


Figure 7. Stresses in a Loaded Beam

It is assumed, and for homogeneous beams without initial internal stress can be demonstrated to be true, that up to the elastic limit a vertical plane section before bending remains plane while under bending stress. However, when the more highly stressed outer fibres reach the elastic limit they yield and do not take stress so rapidly, while the fibres underneath are progressively nearing the elastic limit and a condition of overstrain as the load increases. At any rate distortion results and a plane section no longer remains plane, and stress distribution depends to a large extent upon the comparative ductility of various parts of the section.

If a tension failure starts in a brittle material, total failure is generally complete and immediate as is evidenced by the flexure failure of cast iron, chalk, or glass. However, if a tension failure starts in a ductile material it may progress indefinitely until the ductility is gone and then crack, or else the increasing compressive stress may cause buckling of the fibres on the compression side.

Compression failure often appears in concrete beams, over-reinforced on the tension side (Figure 8A). Local compression under the load often develops in a wooden beam especially when the wood is green or wet. This may develop to cause failure or may be arrested so much that final failure will occur in some other way (Figure 8B).

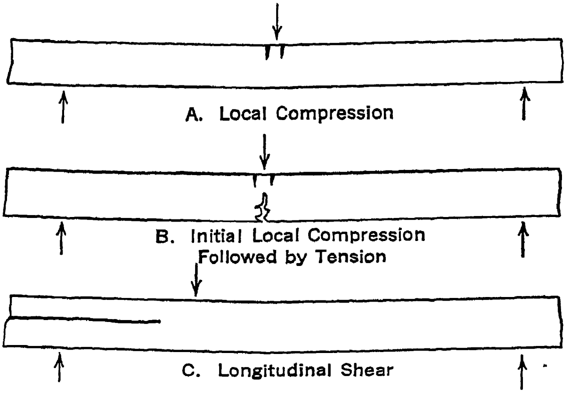


Figure 8. Types of Beam Failures

In short, thick beams, shear near the supports is generally large, and a wooden beam, having low resistance to shear parallel to the grain, is apt to fail by longitudinal shear (Figure 8C).

In the case of a concrete beam of the last mentioned type, the resistance to shear is relatively large but the resistance to the principal tensile stress in the region near the supports is low, and failure parallel to the principal tension planes occurs as "diagonal tension." (See Figure 9.) Such a beam is generally specifically reinforced against such failure.

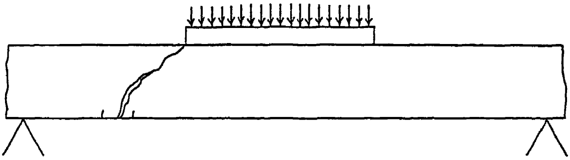


Figure 9. "Diagonal Tension" Failure in a Concrete Beam

On the other hand, in the case of a deep, thin-webbed, steel girder the material is sufficiently strong to withstand the diagonal tension but, being so thin, the web will be apt to buckle under the action of diagonal compression; the "waves" of the buckling being parallel to the principal compression planes. Such girders are usually reinforced with "web stiffeners."

Column Action.—Compression members of considerable length and relatively small cross-section, or lateral dimension in any direction, do not fail by direct compression, but by buckling, and the amount by which the allowable stress must be reduced to allow for this buckling effect is roughly proportional to the ratio of the length to the least radius of gyration, i.e., L/r, which is known as the "slenderness ratio." One commonly used formula for calculating the safe stress for a structural steel column is $P/A = 16{,}000 - 70L/r$. There are many other formulas based on slightly different assumptions but all accomplishing approximately the same results. Any text on the mechanics of materials will contain a discussion of column action theory and a development of various types of formula.

Resilience.—Resilience is the work which a body can do by elastic recovery after a deforming force has been removed. When stresses have not exceeded the elastic limit the energy stored in the body, that is, the resilience, is equal to the work of the forces required to deform the body. If a body is stressed beyond the elastic limit, some of the work is used up in permanently deforming the body and the heat of friction work is dissipated by radiation or convection. In the case of overstrained bodies, the resilience is that proportion of the total work of deformation which the body can give back upon removal of the forces.

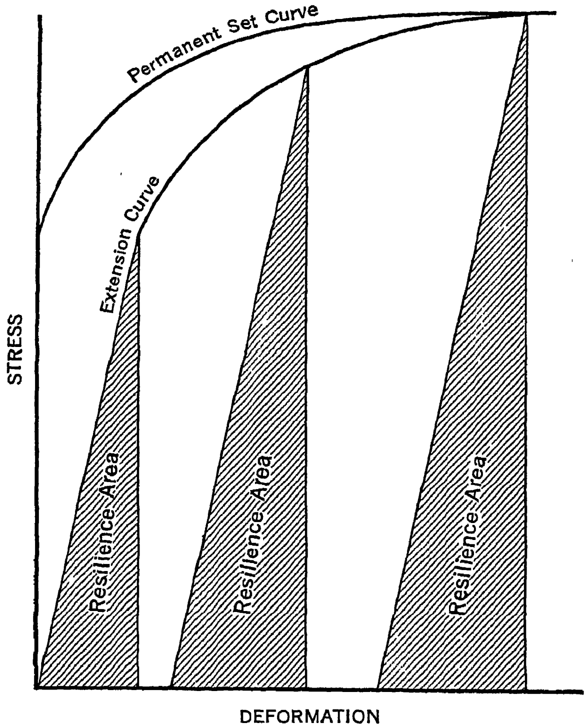

Permanent Set Curve
Extension Curve
STRESS
Resilience Area
Resilience Area
Resilience Area
DEFORMATION

Figure 10. Resilience at Different Stages

In plotting the stress-deformation diagrams, *stress values* are usually selected for *ordinates* and *deformation values* for *abscissæ* so that the area under a curve plotted in this way would represent the work of deformation. The total area under the complete curve, plotted to rupture, would be the total work to produce rupture, and is often called the "energy of rupture." In Figure 10, the three shaded areas indicate the resilience at three different stages, while the total area under the extension curve would represent the energy of rupture. It can be shown that the area between the permanent set curve the extension curve and an abscissa also represents the resilience.

Shock Loading.—Shock loading is the term used to express the effect of a blow, or of a falling body, in producing a load upon a structure or structural element. This type of loading differs from static loading in that *static loading is a direct and usually slow application of force,* while in *shock loading the energy of a suddenly applied shock can only be translated into stresses by "energy" methods.*

In pure static loading there is always perfect equilibrium between the applied forces and internal stresses of a member. This is not the case in shock loading where kinetic energy must be absorbed by the member resulting in vibration. It seems natural to suspect that the energy of rupture as determined by the static test would be a measure of the ultimate resistance to shock load. This, unfortunately, is only approximately the case, because the resistance to fracture and deformation from shock load is much more affected by differences in the physical structure than in the case of static loads. Furthermore, the "time element," which has so great an effect in many engineering considerations, seems to play a very important part in shock resistance.

Hardness.—Hardness is a much abused term, or at least a much misunderstood term, because it is used loosely and indefinitely. In general, hardness means resistance of some kind, but in order to be definite the kind of hardness must be specified.

The old Moh's scale of hardness referred to the relative resistance to scratching, and is sometimes referred to as *scratch hardness.* Then there is the resistance to the action of cutting tools, often referred to, in the metal trades at least, as machinability. However, the most common type of hardness, particularly as applied to the materials of construction, is the *penetration hardness.*

The Brinell hardness tester measures the penetration of a 10 mm. hardened steel ball under a definite, predetermined load. The Brinell hardness number is the actual pressure in kg. per sq. mm. on the surface with which the ball was in contact.

The Rockwell hardness tester measures the penetration of a diamond point or a hardened steel ball. The Rockwell hardness number is an arbitrary figure proportional to the depth of penetration under a definite load.

The Shore Scleroscope is based on the principle of resilience. The Scleroscope hardness is measured by the height of rebound of a small hammer dropped from a definite height. It might be said that it measures the ratio between the elastic dent and the total dent made by the hammer. Physicists would say that it depends on the coefficient of restitution.

Another type of hardness recently advanced is the *work hardness.* Work hardness is measured by reference to the effect of the oscillations of a special pendulum supported by and swinging on a ball in contact with the metal to be tested.

Rockwell and Brinell hardness numbers are the ones most commonly met with.

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Seely, F. B. "Resistance of Materials." John Wiley & Sons.

CHAPTER 2

WOOD FOR STRUCTURAL PURPOSES

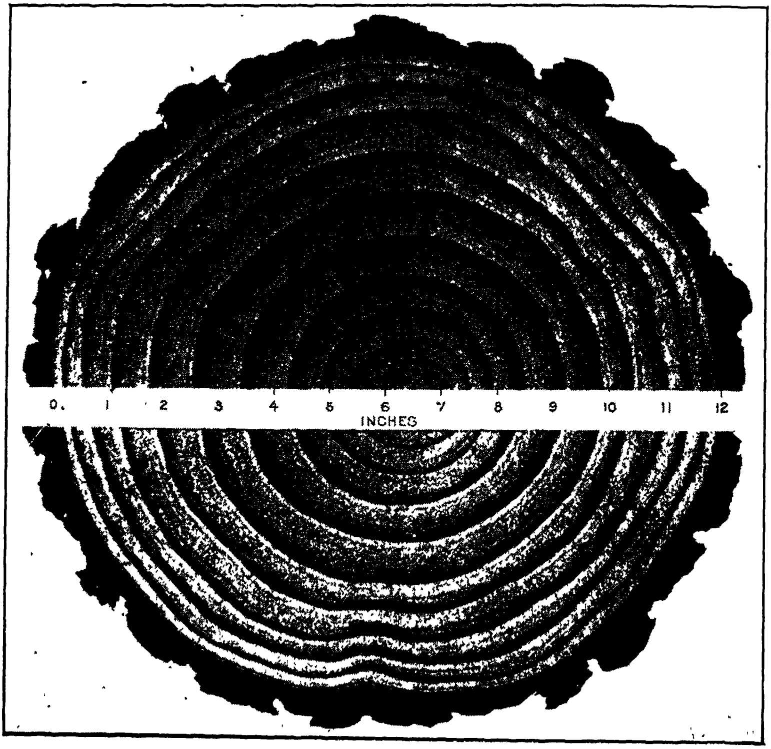
Timber and Lumber.—The word "timber" is, in general, rather loosely used. It may refer to standing trees of considerable size or it may refer to the larger sizes of the product of the sawmill.

Lumber includes about all of the wood used for construction purposes except lath and shingles. However, in the smaller sizes, where strength and stiffness are the important factors, the word timber is often used.

Wood: The Material.—Wood, of course, comes from trees, but it may be the product of either of two distinct processes of growth. Some trees grow by the process of formation of new fibre intermingling with the old, so that they gradually expand as the new wood is formed within the mass of the original material. Such trees are called *endogens.* Very little structural material comes from this class of tree and about the only examples with which we are likely to be familiar are the palm and the yucca.

The other type of growth is by the formation of new cells just under the bark and around the wood previously formed. This is progressive growth from the outside, and trees of this class are called *exogens.* Practically all of our structural woods are of this class and are easily distinguished by the rings of growth.

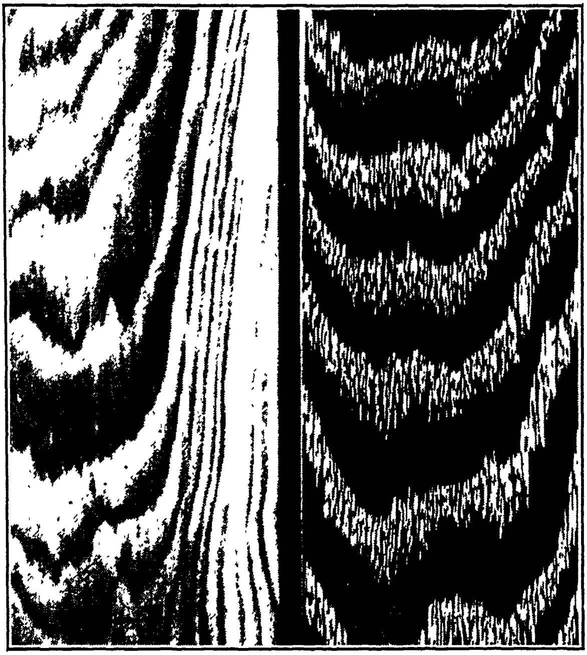
The growth of the exogens is seasonal, and of two kinds more or less distinct. In the spring when the sap flows rapidly and the new leaves and twigs sprout and develop, a rapid formation of relatively large cells under the bark takes place, resulting in the *spring wood.* After this spring growth a period of slower growth through the summer takes place and forms a relatively hard ring of cells called the *summer wood.* The annual growth is always composed of the softer inner portion and the harder outer portion. The two together comprise one of the annual rings. (See Figure 11.) In some trees the difference between the spring and summer wood is very marked, while in others it is very slight. For instance, in hard pine or oak there is a very marked difference in the different parts of the ring, whereas in white pine or basswood there is scarcely



(Courtesy of U. S. Forest Service)

Figure 11. Cross-Section of Loblolly Pine 12 Years Old, Very Rapid Growth Shown in Annual Rings

any difference. When logs are sawed into lumber the rings produce a variation in the appearance of the surface which is known as *grain* and the direction of the cut makes a great difference in the grain.



(Courtesy of U. S. Forest Service)

WHITE PINE RED OAK

Figure 12. Grain of Wood

Hardwoods and Softwoods.—In general the broad leaved trees are classed as the hardwoods and the conifers or cone bearing trees as softwoods. This is a very loose classification, however, for some of the so-called hardwoods, such as basswood, are very much softer than some of the softwoods, such as longleaf pine.

Composition of Wood.—The fibrous structure of wood is essentially the organic material cellulose, impregnated with lignin and some inorganic material which remains as ash, upon ignition. The chemical composition of wood is about 49% carbon, 44% oxygen, 6% hydrogen, and 1% ash. It is about 99% organic material and 1% inorganic.

Moisture in Wood.—Water forms a large part of the cellulose of the wood fibre where it is in chemical union with carbon. It constitutes a large part of the albuminous substances which make up the protoplasm in the living cells. Besides this it saturates the cell walls and it fills more or less completely the pores of the lifeless cells of the heartwood. The water of the sapwood contains traces of mineral salts, and at times traces of sugar, organic acid, and gum.

Heartwood and Sapwood.—The heartwood of a tree is the darker colored portion in which all the life has become extinct. It is not decayed in any sense but simply dead. Further than that, however, there has been some kind of a chemical readjustment which has changed the color and durability of the material. The sapwood is the lighter colored portion under the bark which contains the living cells. The thickness of the sapwood is variable; it may be a few or several rings in thickness. It apparently is a function of the vigor of the tree and it may include more rings on one side of the tree than on the other. The strength and stiffness of the sapwood is about the same as that of the heartwood as long as it remains sound, but it is very much less resistant to decay. The changes that take place in the growing tree, converting the sapwood into heartwood, do not take place after the tree is cut, and seasoning and drying in no way converts the former into the latter.

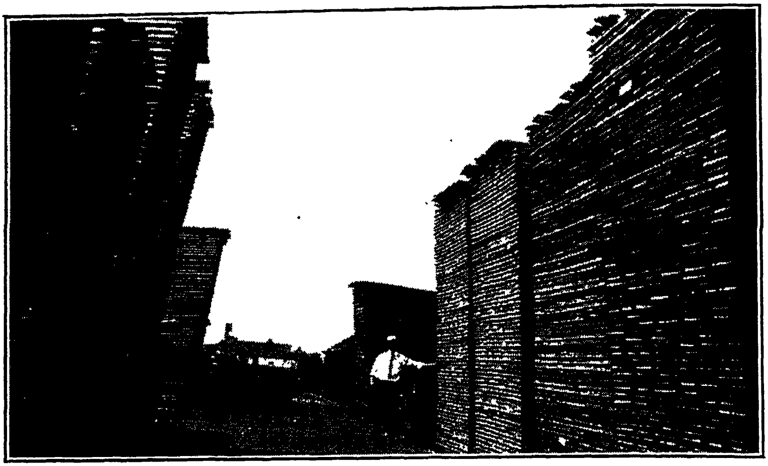
Seasoning and Drying.—In regard to seasoning, Herman Von Schrenk writes in Forestry Bulletin No. 41 as follows:

"Seasoning is ordinarily understood to mean drying. When exposed to the sun and air the water in green wood rapidly evaporates. The rate of evaporation will depend on the kind of wood, the shape of the timber and the conditions under which the wood is placed. Pieces of wood completely surrounded by air, exposed to the wind and sun, and protected by a roof from rain and snow, will dry out very rapidly; while wood packed close together, so as to exclude the air or left in the shade and exposed to rain and snow, will probably dry out very slowly.

"But seasoning implies other changes besides the evaporation of water. Although we have as yet only a vague conception as to the exact nature of the difference between seasoned and unseasoned wood, it is very probable that one of these consists in changes in the albuminous substances in the wood fibre and possibly also in the tannins, resins, and other incrusting substances. Whether the change is merely a drying out, or whether it consists in a partial decomposition, is as yet undetermined. That the change during the seasoning process is a profound one there can be no doubt, because experience has shown again and again that seasoned wood fibre is very much more permeable, both for liquids and gases, than the living, unseasoned fibre. One can picture the albuminous substance as forming a coating which dries out and possibly disintegrates when the wood dries. The drying out may result in considerable shrinkage, which may make the wood fibre more porous. It is also possible that there are oxidizing influences at work within these substances, which result in their disintegration.

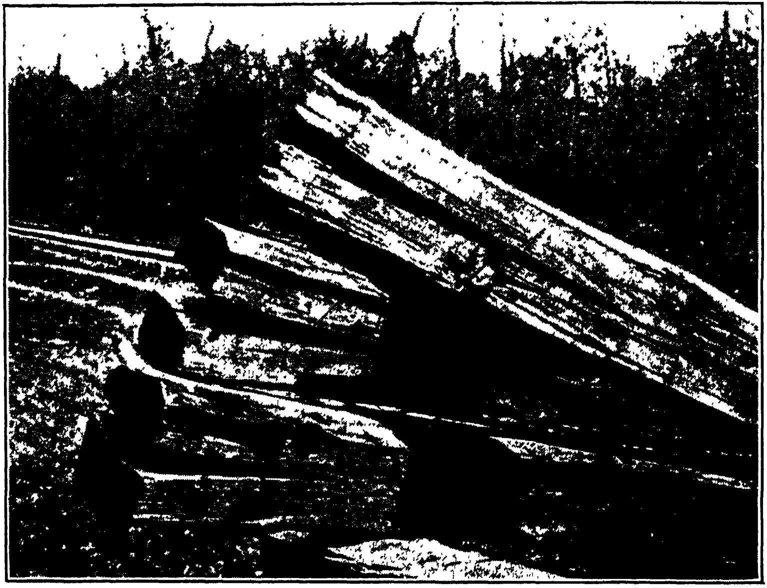
"Whatever the exact nature of the changes may be, one can say without hesitation that exposure to the wind and air brings about changes in the wood which are of such a nature that the wood becomes drier and more permeable. When seasoned by exposure to live steam, similar changes take place. The water leaves the wood in the form of steam, while the organic compounds probably coagulate or disintegrate under the high temperature."

Air seasoning, when properly carried out, results in very superior material, but unfortunately manufacturers are so



(Courtesy of U. S. Forest Service)

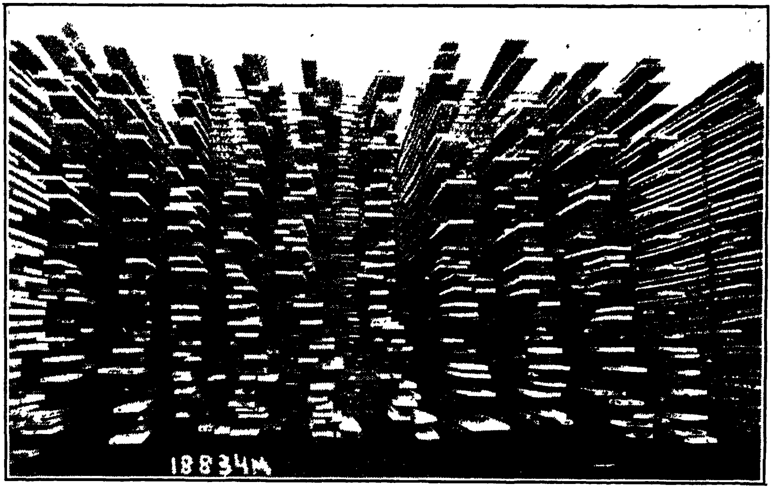
Figure 13. Red Gum and Cottonwood Lumber Piled on Concrete Foundations by Wabash Mfg. Co. Note straight and even course in each pile and absence of end checks



(Courtesy of U. S. Forest Service)

Figure 14. White Oak Ties Seasoned Too Fast

pressed for lumber that they cannot wait for the slow process of proper air seasoning which may take from two months to a year, depending on the species and the conditions of drying. The result is that lumber improperly seasoned is worked into finished construction which is therefore subject to subsequent warping, checking, and splitting.



(Courtesy of Forest Products Laboratory, U. S. Forest Service)

Figure 15. Results of Poor Kiln Drying

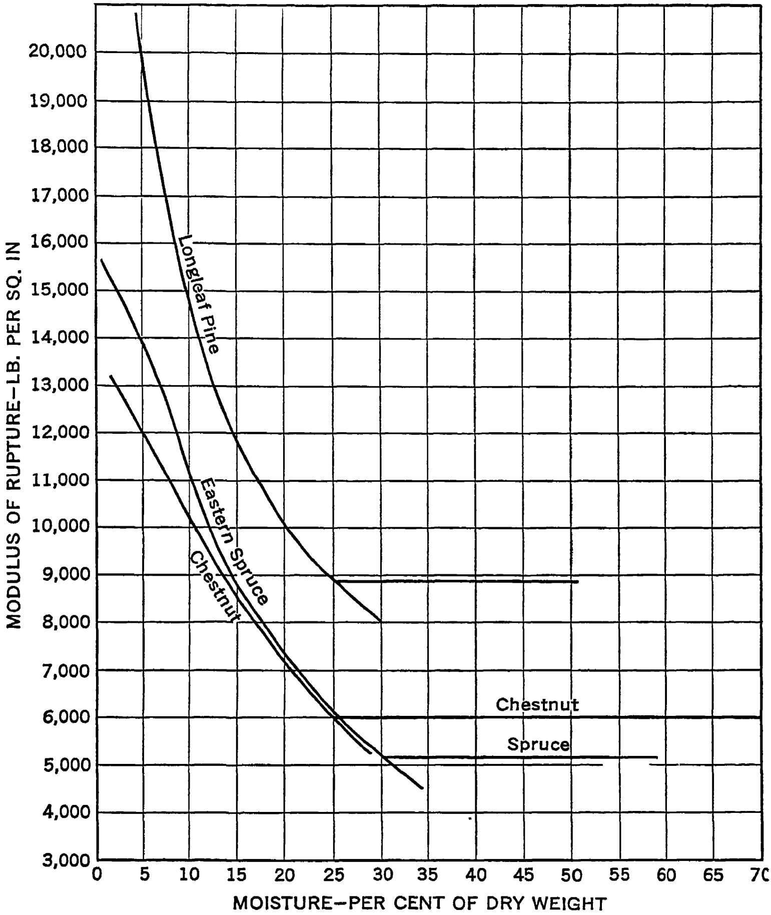
Failure to provide an adequate number of stickers resulted in bowing, twisting, and crooking in this kiln truck load of lumber. The excessively wide flues in the piles tend to produce overdrying in some parts of the kiln, while the non-uniformity of the same channels causes uneven drying.

Kiln Drying.—In order to get properly seasoned wood without waiting for the slow process of air seasoning, a rapid process known as *kiln drying* is customarily used. In this process the lumber to be dried is stacked in a room, or kiln, in such a way that the air may be forced or drawn through it. Circulation of the atmosphere in the kiln is maintained by a fan or blower, and the temperature and relative humidity kept carefully under control. At the beginning of the process the temperature is raised to as high as 180° F., and at the same time steam is introduced until the relative humidity is approximately 100%. These conditions are maintained until the wood is thoroughly heated through and the fibre has become softened so that the moisture diffusion will be rendered relatively easy. The moisture in wood tends to equalize itself by flowing to areas of least moisture. If it is desired to produce a flow of moisture in a piece of wood of uniform moisture content, this uniform condition must first be upset. This is done by circulating the air of proper temperature and humidity around the piece. As soon as evaporation from the surface commences, a "moisture gradient" has been established; that is, the wood has been made drier at the surface than in the interior, and thereby a movement of the moisture from the interior to the surface has been started. If moisture removal from the surface is continued by means of evaporation, a moisture gradient will continue to exist.

Shrinkage: Fibre Saturation Point.—As the drying of the green wood progresses, the amount of free water in the cells gradually diminishes, and soon the cells near the surface have lost all their free water, i. e., they have reached the fibre saturation point.

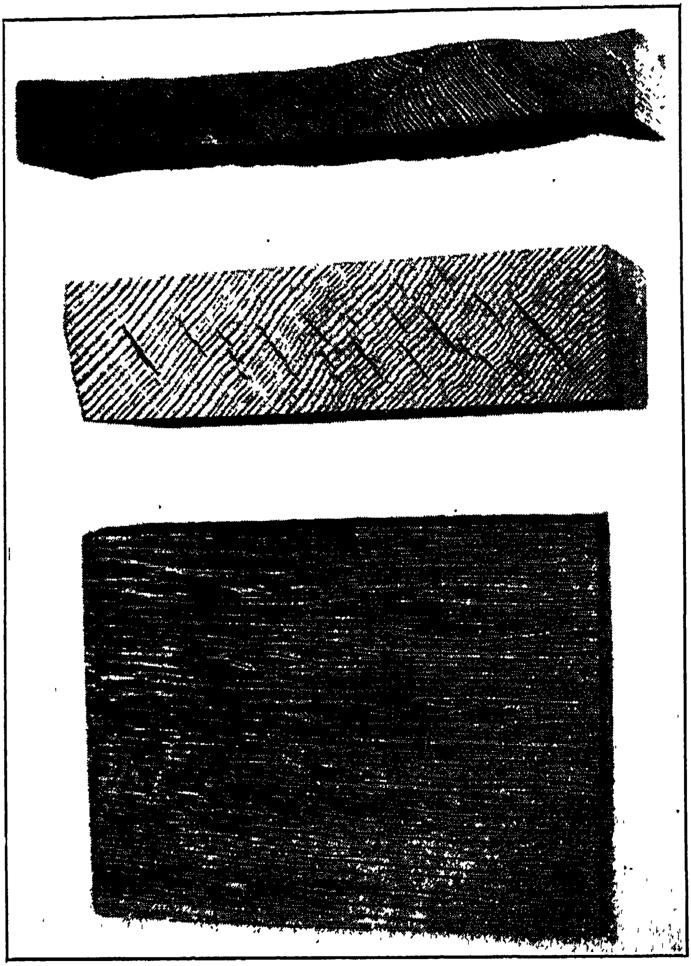
It is at this condition which is a very definite one for most species, usually between 25% and 30% moisture, that the changes in the properties of the wood begin to take place. As wood dries beyond the fibre saturation point, it begins to shrink; and it will continue to shrink as long as it loses moisture. In fact, this shrinkage is very nearly proportional to the amount of drying, below the fibre saturation point. Shrinkage is not uniform, however, for there is practically none parallel to the axis of the tree, and the shrinkage parallel to the circumference is two to three times as great as that parallel to the radius.

Drying Defects: Case-Hardening, Honeycombing, Checking.—Most of the defects ordinarily classed as drying defects would not exist if it were not for uneven shrinkage, and the attendant stresses set up by it. As the outer surfaces of a piece of wood reach and pass the fibre saturation point they begin to shrink and, in so doing, squeeze together all of the green wood inside, since it is not ready to shrink of its own accord. The first result is that the surface layers, in trying to



(From U. S. Forest Service Bulletin No. 70)

Figure 16. Variation of Strength in Wood with Moisture in Bending. The fibre saturation point is indicated where the horizontal line breaks away from the curve



(Courtesy of Forest Products Laboratory, U. S. Forest Service)

Figure 17. Drying Defects in Wood

The upper board is a piece of redwood showing collapse; before drying, the board was of uniform thickness. The piece of Douglas fir plank in the center shows honeycomb. The lower board is a resawed piece of badly honeycombed slash-sawed oak, showing the appearance of honeycomb on the tangential faces.

squeeze the inside, or core, create in it a state of compression, and in themselves a corresponding state of tension.

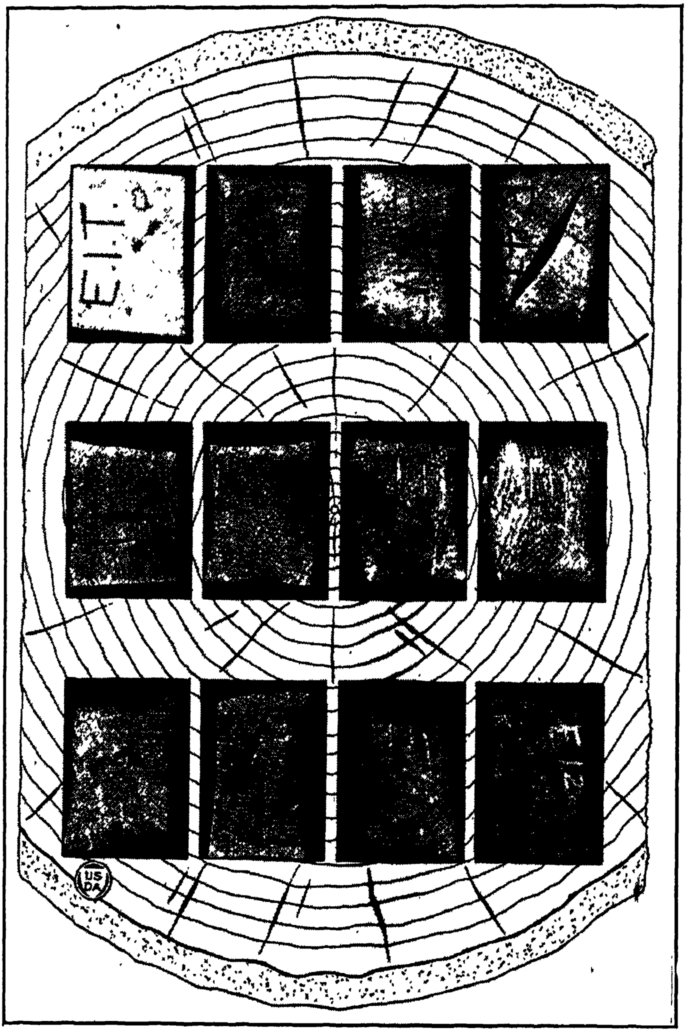
This drying stress will increase as the drying progresses, but eventually the outside fibres become so stiff and hard that they resist the stresses placed on them by further drying and they become "set." Further drying results in a reversal of stresses so that the inner layers are in tension and the outer layers in compression. If special precautions are not taken it is to be expected that most kiln dried stock will be in this condition when removed from the kiln. This condition is usually described as "case-hardened." It has been assumed that the stresses in the wood were not sufficient to cause visible damage, but if the strength of the wood across the grain is not sufficient in tension during the early stages of drying, it will tear open, causing surface checks of varying size and depth. Likewise, if the inner layers are not strong enough to resist the stresses set up in the latter stages of the drying they will rupture, causing "honeycomb" or "hollow horn."

There are several other defects due to uneven shrinkage such as warping and twisting which are caused by various irregularities in structure and drying.

Thoroughly dried wood is several hundred per cent stronger than the green wood as it is first cut. One of the Forestry bulletins (No. 70) shows ratios for comparative strength in compression as follows:

Species	Compression Parallel to Grain 3½% Moisture, Kiln Dry	Compression Parallel to Grain 12% Moisture, Air Dry
Longleaf pine	2.9	1.7
Spruce	3.7	2.4
Chestnut	2.8	1.8
Loblolly pine	3.0	2.0
Red fir	2.6	1.7

Though thorough drying produces an increase of strength which is permanent if the wood remains dry, it also has an in-



(Courtesy of U. S. Forest Service)

Figure 18. Cross-Section of a Southern Swamp Oak Tree Cut into Bolster Stock and Dried

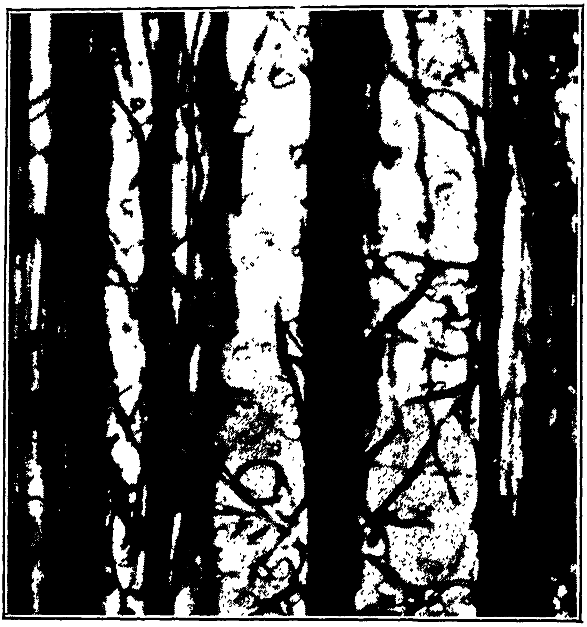
The black rectangles represent the green size and exact location of the pieces in the tree. The dried pieces exhibit, in exaggerated form, many of the common drying defects, such as checks, honeycomb, diamonding, and even cupping. The difference between radial and tangential shrinkage and the comparatively small shrinkage for some of the sapwood are illustrated.

herent weakening effect so that a block which has been dried, and then remoistened, is weaker than one of an equal degree of moisture which has not been dried. For this reason strength values for structural timbers are ordinarily based on the tests of timbers in the green condition. The higher values are only permissible when the material is to be used and kept perfectly dry.

Deterioration of Timber.—The durability of wood is an extremely variable property depending on the species and the conditions to which it is exposed. Decay is the most universally destructive agent, but under the right conditions and in certain localities great injury is often done by attacks of insects, marine borers, rodents, and woodpeckers. Fire should not be omitted from the list, but it is in a class by itself.

Decay.—Under the right conditions certain low forms of plant life, called fungi, grow in wood, and by so doing disintegrate and destroy portions of the wood fibre. As a result of this process the wood changes its physical properties and is called *decayed*. The fungus operates by sending out minute filaments which penetrate the wood fibre and absorb the material of the fibre as they grow. When the fungus has extracted a sufficient amount of material, it forms, on the outside of the wood, fruiting bodies known as punks, or toadstools, containing spores. These spores, when ejected as they ripen, are blown about by the wind to become lodged in cracks and crevices, and thereby infect sound wood. Figures 19, 20, and 21 show such fungi; the latter is of the fruiting body of one of the commonest of these fungi as it appeared on the side of a railroad tie from which the ballast has been scraped for observation.

The conditions necessary for growth and development of wood-destroying fungi are: (1) water, (2) air, (3) organic food materials, and (4) a certain amount of heat. The wood fibre and organic substances found in the living cells of sapwood, such as albuminous substances, starch, sugar, and oils form the food necessary to start the growth of the fungus threads. A further requirement is oxygen; no growth will take place under water, or in the ground at a depth of 2 ft. or more, the depth varying with the characteristics of the soil.



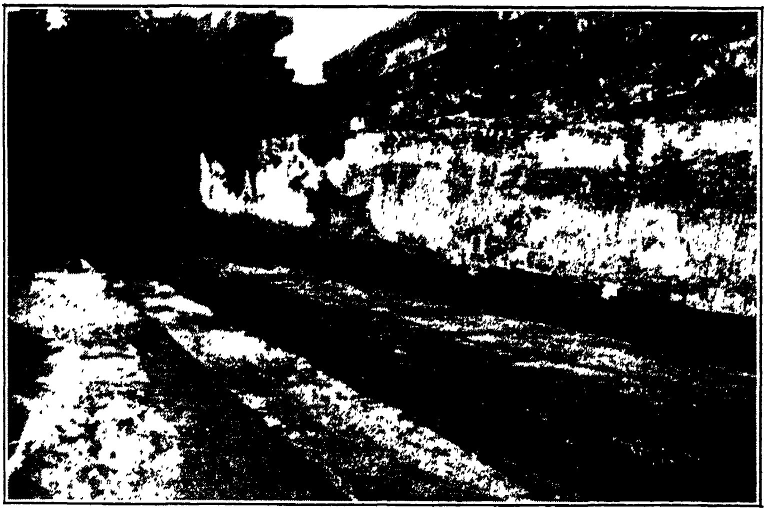
(Courtesy of U. S. Forest Service)

Figure 19. Rotting of Wood Caused by Fungi

The up-and-down lines in this enlargement of southern yellow pine are the walls of the wood fibres and the twisting dark lines between are threads of a common, wood-destroying fungus. The small irregular holes—the whitest spots in the picture—are punctures made in the cell walls by the food-seeking fungous threads. By attacking the cell walls, fungi weaken wood until it crumbles away in the last stage of rot.

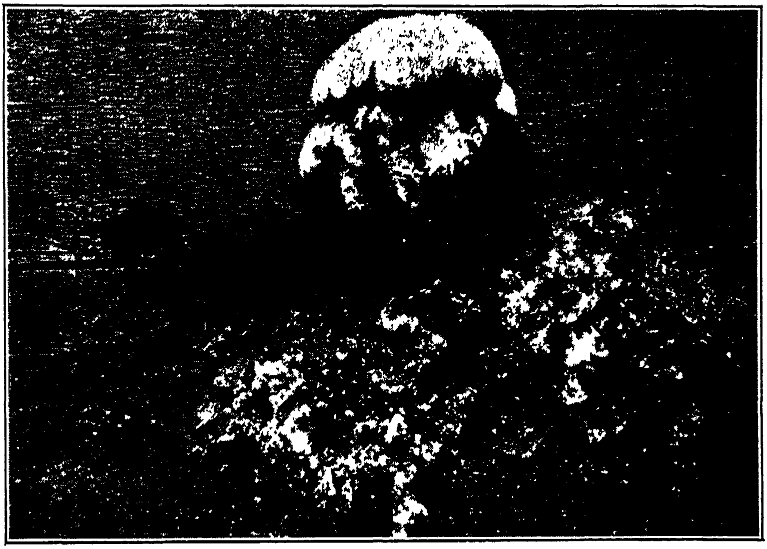
The Forest Products Laboratory of the U. S. Forest Service estimates that an annual saving of more than a billion and a half cubic feet of standing timber could be profitably made by protecting wood from fungi through the use of chemical wood preservatives and through better methods of storing and using wood.

The best examples of this necessity for oxygen can be found in the way in which fence posts and telegraph and telephone poles decay at points just at, or just below, the surface of the ground, where there is a balance between the supply of air and water.



(Courtesy of U. S. Forest Service)

Figure 20. Fungus Growth in Stacks of Yellow Pine



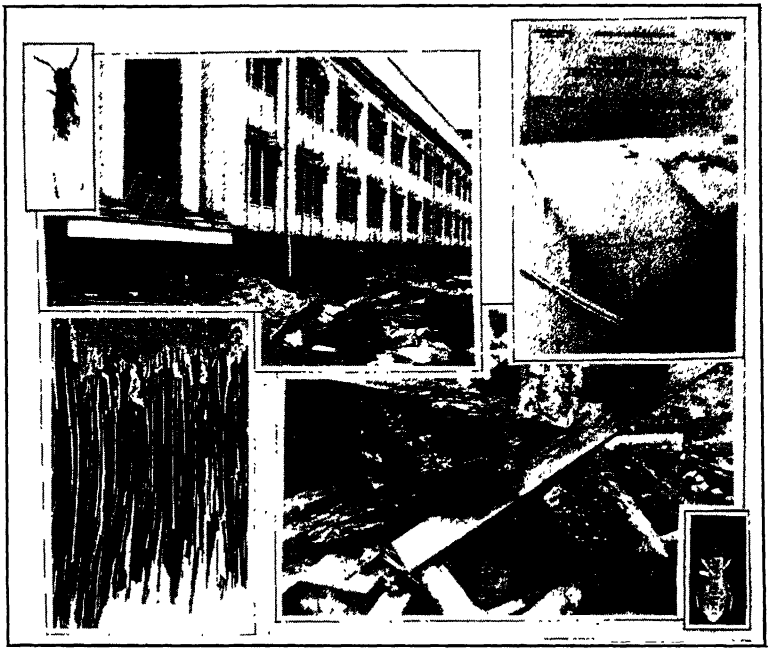
(Courtesy of U. S. Forest Service)

Figure 21. Wood-Destroying Fungus on Red Fir Tie

For practical purposes water is the most important factor. Without water no fungus growth, and consequently no decay, is possible. *Dry rot,* a form of decay in which the wood turns to a dry, brittle, charcoal-like substance, is commonly supposed to take place without any water. Such is not the case, however. The atmospheric moisture is sufficient to permit growth of dry rot fungus even if no moisture is contained in the wood. Too much water will prevent the growth of fungus because it shuts off the air supply. The amount of water necessary for the growth of fungus is very small. Wood freshly cut contains more than enough at all seasons to support fungus growth. From this discussion it will at once become apparent that *dry* wood will not rot or decay.

Insects.—Although decay is the principal cause of deterioration of timber, an immense amount of damage is done by attacks of insects. Timber with the bark on is especially liable to injury from them, and the attack once started in the green log may continue after the wood has been seasoned by the ordinary air seasoning process. Kiln drying if carried on at a high enough temperature will result in the extermination of such life. Insects are particularly active in mine timbers, posts, poles, wagon stock, and pulpwood. Two common insects are the powder post insect and the pole borer. The eggs of these insects are deposited on the surface, and hatch into white grubs, which bore into the wood and fill it full of their tunnels. After a time the grub forms a cavity and stays in it until the final transformation into a beetle. Under certain conditions these insects multiply very rapidly and the deterioration of infested timber proceeds quickly.

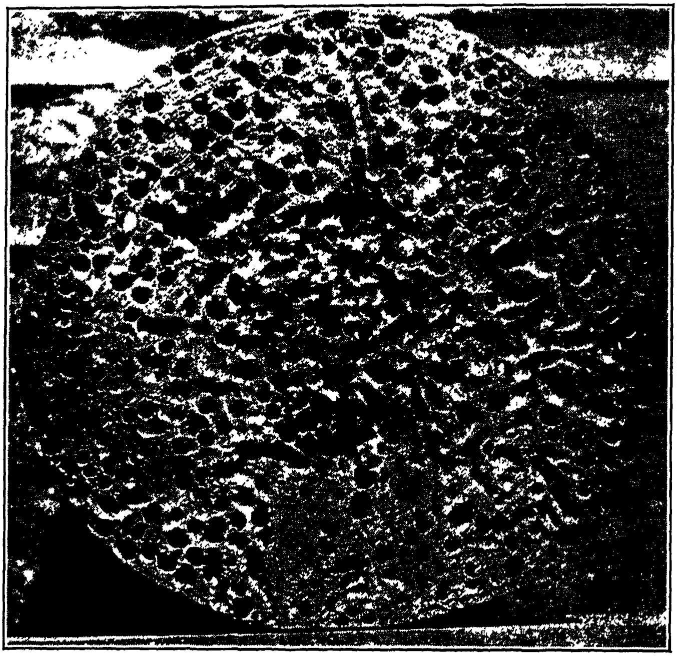
White Ants.—One of the most destructive of insects is the termite, which goes by the name of the white ant and does a great deal of damage in the tropics, both to live and dead timber, though particularly to the latter in dwellings and furniture. These pests often start attacks in a dwelling in the sills through which they work into the frame. They have been known to get into furniture of various kinds, and Baterden reports having seen great numbers destroying the frame-work of a piano, and that not a very old one, in an English dwelling house. They are almost impossible to exterminate, various schemes having been tried but with little success. In Northern Australia where the ants are larger and more destructive than any other place in the world, carbolineum and anti-termite have been tried. These remedies check the ravages of the ants for a time, but they soon lose their efficacy in tropical climates.



(Courtesy of U. S. Dept. of Entomology)

Figure 22. Attack of the Termite Ant

Marine Borers.—There are two classes of marine borers infesting the waters of both Atlantic and Pacific coasts, the mollusk and the crustacean types. The most important of the *mollusk* type are the *toredo* and *xylotrya* which are similar in appearance and in mode of living. These mollusks are commonly called "shipworms" on account of their destructive action on timber ships which had to be copper sheathed for protection. The animal is produced by eggs and is so prolific that the eggs from a single specimen may number a million in a season; they are free swimming in three hours, have a well-developed shell before the end of the day, are very hardy, and nearly all seem to develop to maturity. They tunnel into the wood by means of a pair of shell valves and excrete the borings, and a calcareous substance for the lining of the burrow, through a posterior siphon. The food supply, consisting of low forms



(Courtesy of U. S. Forest Service)

Figure 23. Ten Months' Work of Marine Borers on an Untreated Pile

of animal life found in water, is secured through a second posterior siphon.

The toredo rarely exceeds 15 in. in length and ⅜ in. in diameter, but specimens of the xylotrya 6 ft. long and ¾ in. in diameter have been found. (See Figure 23.) These mollusks work from a little above low water down to the ground, and timber 25 ft. below lowest water level has been found attacked. They work very rapidly and submerged wood is almost immediately attacked. A young toredo has been found in wood submerged eight days. They thrive best under the influence of heat, and in a tropical climate are most destructive; 6-in. timber has been destroyed in six weeks in the Gulf of Mexico, and piles 15 in. in diameter have had to be replaced after six months' service in the same district.

The Limnoria.—The limnoria, sometimes called the "wood louse" or the "boring gribble" is the *crustacean* which is most dangerous to timber. Unlike the toredo, the limnoria lives on the wood fibre, which it destroys. It is found in most parts of the world and always in large numbers together. It grows to about the size of a grain of rice and works at and just under the surface of the wood in a narrow belt near the low water mark. When the wood is tunneled to the depth of perhaps a half inch, it becomes brittle and is washed away, thus affording fresh wood for the animals to work upon. The limnoria often works in conjunction with the toredo, but it also infests the waters of colder seas where the toredo cannot exist, and therefore has a wider range.

The Chelura.—The chelura which resembles a very small shrimp, the *sphaeroma* which works after the fashion of the limnoria and which is somewhat larger than the limnoria, and the *pholas* which resembles the common mussel are other less important species of the timber borers.

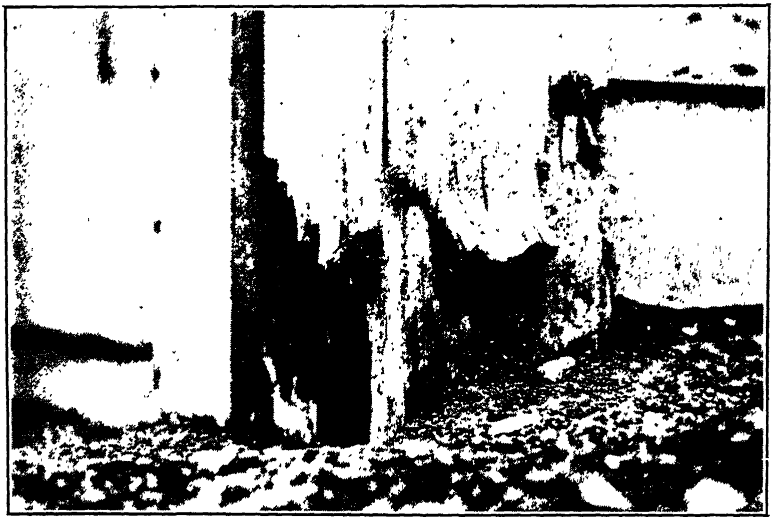
So far as is known, none of these pests will exist in sewageladen water; some will not exist in muddy waters, and they are most destructive in clear, warm, pure sea water.

Rodents.—In certain localities gophers and other similar rodents do considerable damage by gnawing of posts and poles at or near the ground line. Besides directly weakening the material they afford better conditions for the infection by, and growth of, wood-destroying fungi and consequent decay.

Woodpeckers.—Woodpeckers often do considerable injury to poles where they drill holes for nests. If the holes are not too near the bottom they do not directly weaken the poles to any great extent, but they afford an opportunity for the collection of moisture and infection by fungus, ultimately leading to conditions of decay. It is rather surprising to what extent such destruction occurs in certain sections of the country.

Preservation of Timber.—From reports of studies made by the Forest Service, it appears that the life of untreated lumber will vary from 3 to 20 years when exposed to the elements. The lower limit is for material subjected to very bad conditions such as mine props, piles, etc., while the upper limit is for well-drained structural timbering, poles and shingles, etc. It has been estimated that upwards of 20,000,000 board feet of lumber are used annually for replacements of all kinds and that about 1/3 of this amount could be saved if proper preservative methods were practiced. It has been estimated that the net saving in money would approximate not far from $100,000,000 per year in the United States alone. (See Figures 24 and 25.) Still greater economy is possible by proper use of preservatives on account of the fact that many woods which would be inferior in the untreated condition are quite satisfactory when protected by some preservative. Furthermore, it would lead to better forest management, because many locations suitable for some of the more rapidly growing trees would become attractive for reforestation. It would also lead to the clearing of land at present occupied by fire-killed timber which can be effectively used if properly treated.

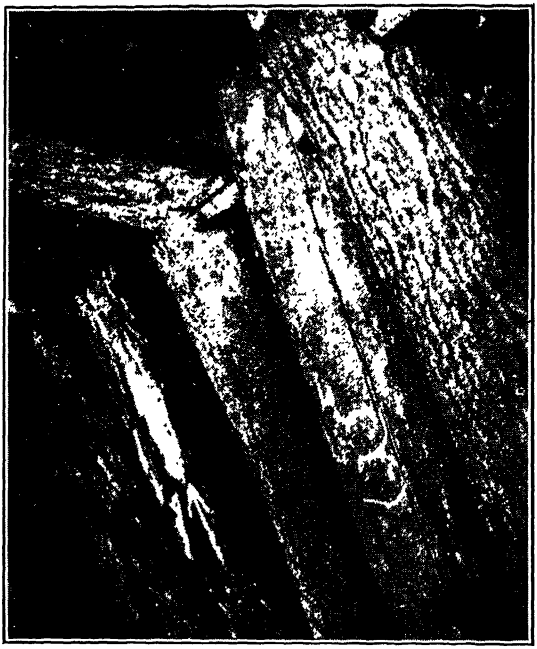
It is desirable that all timber which is to be treated with preservative be thoroughly seasoned so that the penetration of the preservative may be accomplished with the least possible resistance. Under some conditions air seasoning is considered sufficient preparation for the preservative process, but with that exception exposure to saturated steam is the most used preliminary conditioning process.



(Courtesy of U. S. Forest Service)

Figure 24. A Frame Building Corner Post Set Directly in the Soil Without Preservative Treatment

Impregnation of Timber.—J. R. Baterden says: "Methods and processes for the preservation of timber are as old as history. Rot and decay were the bane of the architect and engineer 2,000 years ago as they are today. The famous wooden statue of Diana of the Ephesians was kept saturated with oil of Nard by means of a small number of orifices in the wood-work in order to prevent decay, and even so late as the nineteenth century—so history repeats itself—a famous north-country engineer recommended the coating of piles from the ground level to about low water with whale oil, as a preventive against the sea worm. The Ephesians were probably successful, the engineer was not.



(Courtesy of U. S. Forest Service)

Figure 25. Treated and Untreated Mine Timbers

The mine timber marked "3" was installed after treatment with zinc chloride in 1908 and is still sound after 17 years of service. The untreated timber marked with the arrow is decayed and due for early replacement. This timber was installed four years before the photograph was taken, to replace a treated timber which had been in service for 14 years. The original treated cap of this set, seen supported by the decayed timber, is sound in its eighteenth year of service.

"The first patent for artificial preservation of timber appears to have been taken out in 1738, since which time, as has been truly said, 'almost every chemical principle or compound of any plausibility has been suggested for the purpose.' Britton, in his treatise on Dry Rot in Timber enumerates twenty-nine different substances which had been used for the preserving of wood; at the present time they probably number over 200. Over 120 patents exist in America alone."

In general, there are three processes of preservative treatment: (1) superficial or surface treatment, (2) non-pressure processes of impregnation, and (3) pressure processes of impregnation.

The superficial or surface treatments are the least expensive and also the least effective. The preservative may be applied with a brush, or, if a heavier and more effective treatment is desired, dipping may be used. The superficial treatment has been used considerably for mine timbers, poles and posts. The cost of material in the dipping process is more than for the brush treatment, but the labor cost in the dipping process is the lower. Creosote, paint, oil, and whitewash are the preservatives most often used in such treatments. The creosote should be applied hot, for the best results.

In the non-pressure processes of impregnation, penetration is secured either by absorption or by atmospheric pressure. The penetration is not generally very deep but with some of the softer, more open-grained woods such methods may be effectively used. In this treatment the timber is placed in an open tank and covered with the preservative. In most cases the temperature of the liquid is raised to just above the boiling point of water so that the sap and free moisture is mostly driven from the wood. The temperature is then allowed to drop, or the timber transferred to another tank with cold material in it, and the atmospheric pressure forces the preservative into the wood, following the partial vacuum which is formed as the temperature of the wood drops.

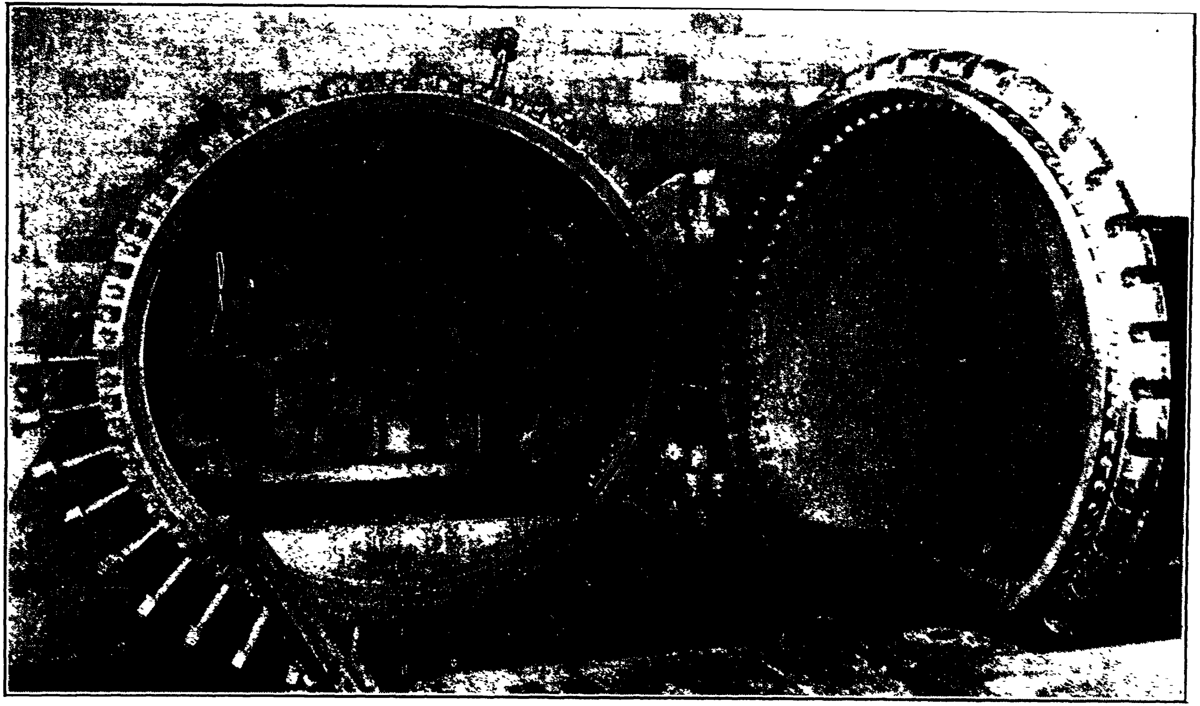
The process may be used with creosote, zinc chloride, or crude oil. A decrease in strength is quite likely, however, if the wood is boiled in the zinc chloride solution.

Kyanizing.—Kyanizing is a non-pressure process in which the preservative is a 1% solution of bichloride of mercury (corrosive sublimate). Boiling is not resorted to in this case, but the wood must be very thoroughly seasoned. After a period of soaking of 9 or 10 days, the depth of penetration is about ¼ in.

Where timber is used in dry locations this process is effective, but owing to the poisonous nature of the salt it is dangerous to apply, and dangerous to use, especially in case of locations where it is likely to be licked by animals. This process has not been used very much in the United States, but in England and Europe it has been used a great deal. Timber treated in this manner is often painted in order to keep the salts from leaching out. As a matter of fact, this process is often used as a pressure process in the European countries.

The *pressure processes* are the most satisfactory for treating large amounts of timber and are the only ones that can be successfully used with many kinds of wood, such as hemlock, Douglas fir, and redwood. (See Figure 26.)

Burnettizing or the Zinc Chloride Process.—Burnettizing was invented in 1838 by Sir William Burnett, and has been used considerably ever since. It was at first favored by the British government but has lost its standing. It is, however, much used on the continent for preservation of railway ties, and has been extensively used in the United States for the same purpose. Also on account of its cheapness it is used extensively in mill construction where there is no danger of leaching out the salt by excess water, but where a preservative is very necessary to prevent decay. Another advantage of the zinc chloride process is that the surfaces may be painted, for the sake of appearance, whereas paint on creosoted lumber would become stained and unsightly in a very short time. The solution consists of 2% to 5% of zinc chloride in water, and about ½ lb. of the salt per cu. ft. is the average impreg-



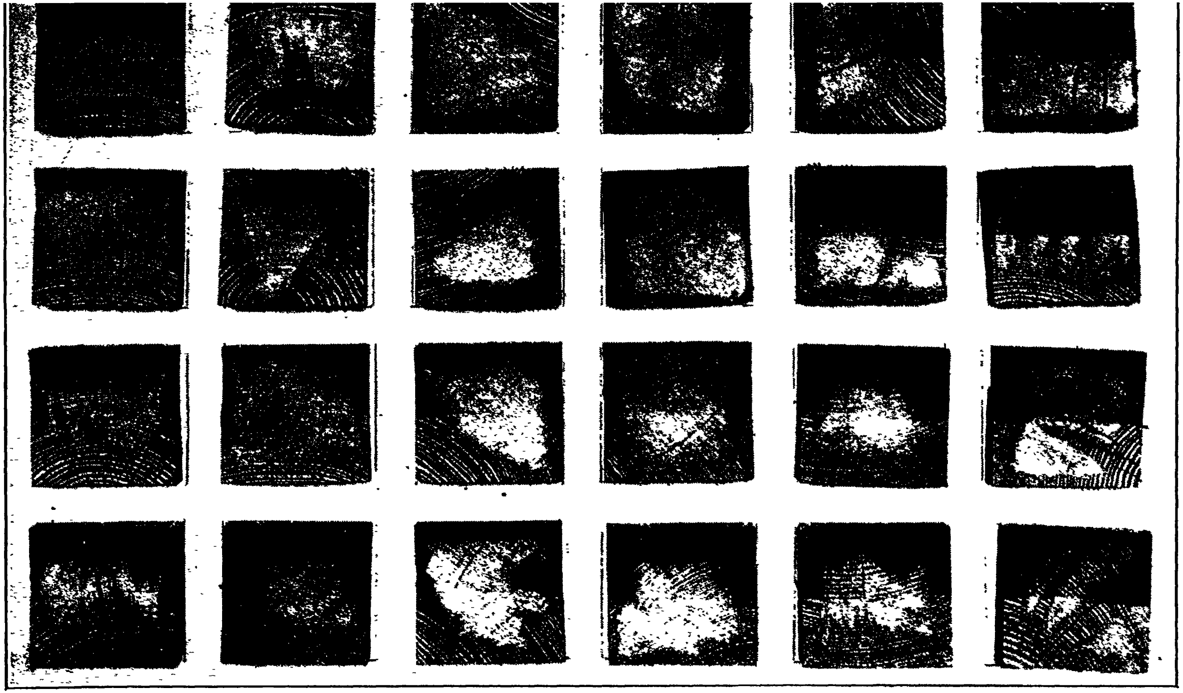
(Courtesy of U. S. Forest Service)

Figure 26. Loading End of Preserve Treating Cylinder at Plant of New England Wood Preserving Co.

nation. The solution is forced into seasoned timber under a pressure of about 150 lb. per sq. in.

Bethell or Full Cell Process.—This process was invented by John Bethell in 1838, the same year that Burnettizing was invented. It is carried out in the same manner except that the preservative used in this case is hot creosote. The timber is generally placed on cars and run into long cylinders where the process is carried out under perfect control. In this process the hot oil is forced in under a pressure varying from 100 to 180 lb. per square inch and the pressure is maintained until the desired penetration is secured when the excess oil is drawn off and the wood allowed to drain for a few minutes before being withdrawn from the cylinder. This process is especially valuable where a heavy impregnation is necessary as is the case with piling and wood block paving. The amount of oil retained varies from 10 to 20 lb. per cu. ft., according to the species treated and the penetration. The cost of treatment is therefore very high, for instance in the case of cross ties where it will average not far from $1.00 per tie. (See Figure 27.)

Rueping or Open Cell Process.—This is one of the most important processes both in the United States and abroad. It is designed to gain the advantage of deep penetration with small absorption of the preservative. Air seasoned material is preferred for this treatment, although steam treated material may be used. After being placed in the treating cylinder, the wood is subjected to action of compressed air, and the cells become filled with air at a pressure of about 75 lb. per sq. in. Creosote oil is then admitted at slightly higher pressure until the charge of wood is completely immersed and then the pressure is increased to 150 lb. per sq. in. or more. It is important that the wood be completely immersed before the pressure is increased, otherwise there would be no excess pressure to secure penetration against the air in the cells. After the proper



(Courtesy of U. S. Forest Products Laboratory, U. S. Forest Service)

Figure 27. Sections Cut from Creosoted Timbers Show Varying Degrees of Penetration Resulting from Variations in the Steaming Period During Treatment

amount of oil has been injected, the oil is forced out and the pressure reduced, allowing the compressed air in the cells to expel a large amount of the oil. It is thus possible to secure a deep penetration and at the same time to leave an effective coating on the cell walls with only about ⅓ to ½ the amount of the oil necessary in the full cell process. Timber treated by this process costs about 30% less than that treated by the full cell process.

A modification of this process is called the *Lowry process*. It is practically the same as the Rueping process, the only difference being that the initial compressed air treatment is not given, but after the pressure is released a vacuum is drawn instead until the surplus oil has been removed. This adds a little expense but the process has found considerable favor, especially for treating ties.

Card Process.—This process was developed to combine the advantages of the zinc chloride process with those of the creosote process. In this process the timber is run into the tank and a vacuum is drawn for about an hour, after which a mixture of 15% to 20% creosote with a solution of 3% to 5% zinc chloride is forced in at a pressure of about 125 lb. per sq. in., and the pressure maintained for several hours. By this means an absorption of zinc chloride about equal to that of the Burnettizing process is secured, together with a penetration of 3 to 5 lb. of creosote per cu. ft. This process costs about one-third as much as the full cell process and has found considerable favor in some localities.

Creosoting, in general, is the most effective method of preservation against decay and the attacks of animal life, in fact it is the only preservative of any use in timber structures in the worm-infested parts of the coast. It is so effective that piles in the Gulf of Mexico, which would have been destroyed in a few months if left in the untreated condition, have withstood the attack of the toredo for 25 years.

Two objections to creosoting are that it can only be used to advantage in outdoor work and that it takes a long time to dry; but the greatest objection, and the main one sometimes, is its very inflammable nature.

Fireproof Timber.—The inherent inability of wood to resist the attack of fire has led to a campaign against its use, aided by those interested in marketing substitute materials. Further than that the use of wood as a building material has been prohibited to a certain extent in congested districts where the fire risk is high. All this has led to an attempt to produce a highly fire-resistant wood, which has come to be known in the trade as "fireproof wood."

The commercial treatment of wood to render it "fireproof" had its beginning in New York City, where in 1895 Bechert treated timbers for use in warship construction for the U. S. Navy. The Navy discontinued its use after a short period, largely because of the corrosive action of the chemicals used, especially when the treated wood became damp, but the City of New York adopted a requirement in 1899 demanding the use of "fireproof" timber in the construction of all buildings over 12 stories high.

Several treating plants sprung up in and around New York where practically all of the market for such material was located. Plants at Philadelphia and Montreal were also apparently in operation about 1903. The curtailment of building operations during the World War practically canceled the market for this material, but since that time a considerable expansion of the market has taken place. Several plants are in operation in or near metropolitan New York and a plant in Los Angeles is reported to be treating timber for fire retardation.

Considerable market for "fireproof" timber is reported from Boston, Philadelphia, and other eastern cities. The merits of this material for museums, theaters, and private estates has apparently been recognized by architects and engineers to such an extent that they are beginning to specify "fireproof" wood for such use.

While it is true that there is some variation in the ease with which various species of wood will be consumed by fire, all will readily ignite at about 750° F. This temperature is far less than the 1,700° F. which is the estimated temperature of a burning building and so it is evident that in the end it makes little difference just what species of wood is used in ordinary construction.

Retardants for Fireproofing.—The problem of the "fireproofing" of timber is to find a treatment which will control the combustion of gases evolved, when the wood becomes highly heated. Three methods of action of the retardant have been in use as follows: (1) retardants liberating steam or water vapor, which tends to dilute the combustible gases from the wood; (2) retardants which, by giving off a non-combustible gas, dilute or combine with the combustible gases from the wood; (3) retardants which act by fusing and forming a non-volatile residue resulting in a fluid coating on the wood, thereby preventing the access of the air necessary to support combustion.

Retardants in the first group are generally considered of little value; those in the second group are generally considered as most efficient. Some have the combined effect of two or all three of the above described actions.

Most of the retardants have been water soluble salts and great secrecy has surrounded the processes. The most effective and acceptable chemicals in general use seem to be ammonium phosphate and ammonium sulphate (either alone or mixed) and sodium borate (alone or mixed with ammonium sulphate). Ammonium chloride, ammonium alum, and ammonium sulphate were also effective.

Other experiments have found other chemicals to possess good fire retardant properties but there is some question as to their ability to meet other requirements.

Impregnation of timber is accomplished in the same manner as in the processes already described for ordinary preservatives and most of them are single process methods. In one method, found to be effective, a double process was used, first a solution of sodium borate (borax) was used and then zinc chloride. The two chemicals reacted to form insoluble zinc borate, which fuses when heated and prevents access of the air. The drawback to this method is its expense which is apparently prohibitive.

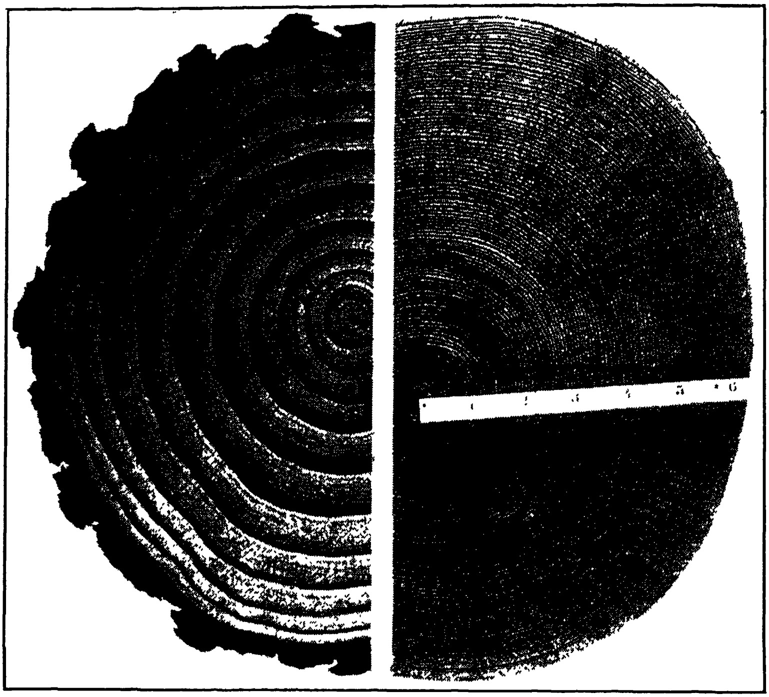
At present the cost of "fireproofing" timber is $75 to $100 per 1,000 ft. b.m., but the market of about 3,000,000 ft. in New York (1927) together with a small market elsewhere has caused considerable competition which will undoubtedly produce a reduction in the cost which will in turn be apt to create a more widespread demand for "fireproof" wood in various types of construction.

Standard Names for Structural Timber.—(Data by the American Society for Testing Materials.)

SOUTHERN YELLOW PINE. This term includes the species of yellow pine growing in the southern states from Virginia to Texas, that is, the pines hitherto known as longleaf pine (Pinus palustris), shortleaf pine (Pinus echinata), loblolly pine (Pinus taeda), Cuban pine (Pinus heterophylla), and pond pine (Pinus serotina).

Under this heading two classes of timber are designated: (a) dense southern yellow pine and (b) sound southern yellow pine. It is understood that these two terms are descriptive of quality rather than of botanical species.

(a) Dense southern yellow pine shall show on either end an average of at least six annual rings per inch, and at least ⅓ summer wood, or else the greater number of rings shall show at least ⅓ summer wood, all measured over the third, fourth, and fifth inches on a radial line from the pith. Wide ringed material excluded by this rule will be acceptable, provided that the amount of summer wood as above measured shall be at least one-half.



(Courtesy of U. S. Forest Service)

Section of loblolly pine, 12 years old, showing very rapid growth.

Section from average longleaf pine tree.

Figure 28. Sections of Pines. Both trees about the same diameter but the difference in the rate of growth is very striking.

The contrast in color between summer wood and spring wood shall be sharp and summer wood shall be dark in color, except in pieces having considerably above the minimum requirement for summer wood.

(b) Sound southern yellow pine shall include pieces of southern pine without any ring or summer wood requirement.

Longleaf and Cuban pine are, in general, heavy, hard, tough, stiff, and very strong woods. They are highly durable in dry localities and fairly so in contact with the ground. When subjected to hot fire, timbers of these woods char on the outside and retain their strength for a long time. (These timbers are used in the so-called slow-burning type of mill construction.)

The other members of the southern pine group are more variable. Most of the specimens of the latter are inferior in structural properties to longleaf or Cuban pine, but they generally possess good strength and durability when not in contact with the ground. The southern yellow pines are the most important source of dimension timber for all heavy construction. They also provide much lumber for various minor purposes. When treated with preservatives the harder woods of this group make good ties and paving blocks.

DOUGLAS FIR. The term "Douglas fir" is to cover the timber known likewise as yellow fir, red fir, western fir, Washington fir, Oregon or Puget Sound fir or pine, northwest and west coast fir.

Douglas fir is strong, but brittle; it is fairly durable but burns easily. It is the best structural timber of the northwest, and is becoming quite common in the eastern markets. It is clear and generally straight grained, although now and then a timber with a dangerous "cork screw" grain appears. It is used in building construction, for dimension timber, ties, piles, boats, paving blocks (when treated), tanks, conduits, and furniture.

NORWAY PINE. To cover what is known also as "Red Pine." Norway pine is cut principally in the states bordering the Great Lakes. It is a rather light wood of fair hardness and strength, but is not durable, especially in contact with the ground. It is often sold for white pine.

HEMLOCK. To cover all southern and eastern hemlock; that is, hemlock from all the states east of and including Minnesota.

WESTERN HEMLOCK. To cover hemlock from the Pacific Coast, otherwise known as hemlock spruce, western hemlock spruce, western hemlock fir, Prince Albert fir, gray fir, and Alaska pine.

Hemlock is light, soft, and brittle. The western variety is moderately strong and fairly durable, and its possibilities are often underrated, but eastern hemlock is weak and not durable in contact with the ground. Hemlock holds nails well and is much used in house framing. Western hemlock is considerably used for dimension timber and cross ties.

SPRUCE. To cover eastern spruce; that is, the spruce coming from points east of and including Minnesota.

WESTERN SPRUCE. To cover the spruce timber from the Pacific Coast. The woods of the spruces are very much alike; they are light and soft and have low strength but are fairly durable. Although size for size they have low strength as compared to longleaf pine for instance, weight for weight they are quite strong and resilient. Good white spruce is the best wood for aeroplane work. Much spruce is used for house building construction; a great deal for paper pulp, and railway ties.

WHITE PINE. To cover the timber which has hitherto been known as white pine from Maine, Michigan, Wisconsin, and Minnesota. White pine is a soft, uniform, white wood, which shrinks very little in seasoning, is easily worked, receives nails without splitting, and takes paint well. It is not very strong but quite durable. For use as window sash, interior trim, and *pattern making,* the demand for this species of wood is very great.

IDAHO WHITE PINE. The variety of white pine from Montana, northern Idaho, and eastern Washington. It is somewhat inferior to the other kinds of white pine.

WESTERN PINE. To cover the timber sold as white pine coming from Arizona, California, New Mexico, Colorado, Oregon, and Washington. This is the timber sometimes known as "Western Yellow Pine" or "Ponderosa Pine" or "California White Pine" or "Western White Pine." This wood is lighter, softer, weaker, and has less durability than longleaf pine, but is heavier and stronger than white pine. It is considerably used for building construction, ties, and mine timbers; it is better fitted for trim or for an inferior grade of pattern stock.

WESTERN LARCH. To cover the species of larch or tamarack from the Rocky Mountain and Pacific Coast regions.

TAMARACK. To cover the timber known as "tamarack" or "eastern tamarack" from the states east of and including Minnesota. Larch and tamarack are of medium weight, are rather tough, hard, and durable. It is not as good a material as Douglas fir or western hemlock. It is used somewhat for lumber and lath, cross ties, and poles.

REDWOOD. To include the California wood usually known by that name. It is light, soft, straight grained and very durable. It is used for all kinds of lumber: ties, shingles, poles, tanks, paving blocks, and conduits.

WHITE OAK OF COMMERCE. Includes true white, post, burr, overcup, swamp, white, cow, and chestnut oaks. This supply comes from states east of Colorado, but mainly from the Virginias, Tennessee, Arkansas, Kentucky, Ohio, and Missouri. These oaks are all hard, heavy, strong, tough, dense woods which are durable in contact with the soil. They shrink considerably in seasoning and are therefore liable to check. White oak is much used for furniture, cross ties, agricultural implements, fence posts, wagon stock, etc. These oaks are the most valuable of the hardwoods.

RED OAK OF COMMERCE. Includes red, pin, Spanish, and black oaks. The sources of supply are the same as for the white oaks. The wood of the red oaks, though hard and strong, is more porous, somewhat lighter and weaker, and far less durable in contact with the soil than white oak. When impregnated with preservative, red oak timber makes excellent cross ties.

LIVE OAK. Found along the coast of the southern Atlantic and Gulf states, in California and Oregon. The wood is heavy, hard, tough, strong, durable, and difficult to work. It is used for implements, wagons, and shipbuilding.

Standard Defects in Timber.—The American Society for Testing Materials gives the standard defects in timber as follows:

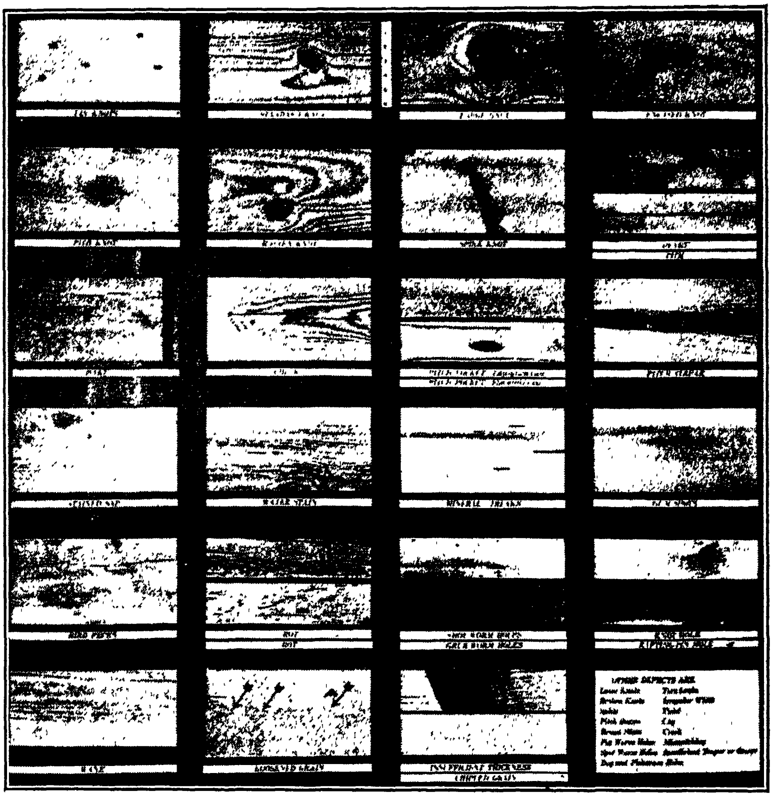
"Measurements which refer to the diameter of knots or holes should be considered as referring to the mean or average diameter.

"SOUND KNOT. A sound knot is one which is solid across its face and which is as hard as the wood surrounding it; it may be either red or black, and is so fixed by growth or position that it will retain its place in the piece.

"LOOSE KNOT. A loose knot is one not firmly held in place by growth or position.

"PITH KNOT. A pith knot is a sound knot with a hole not more than ¼ in. in diameter in the center.

"ENCASED KNOT. An encased knot is one whose growth rings are not interwoven and homogeneous with the growth rings of the piece it is in. The encasement may be partial or



(Courtesy of Forest Products Laboratory, U. S. Forest Service)

Figure 29. Defects Recognized in the Commercial Grading of Lumber

complete; if interwoven partially or so fixed by growth or position that it will retain its place in the piece, it shall be considered as a sound knot; if completely intergrown on one face it is a watertight knot.

"Rotten Knot. A rotten knot is one not as hard as the wood it is in.

"Pin Knot. A pin knot is a sound knot not over ½ in. in diameter.

"STANDARD KNOT. A standard knot is a sound knot not over 1½ in. in diameter.

"LARGE KNOT. A large knot is a sound knot, more than 1½ in. in diameter.

"ROUND KNOT. A round knot is one which is oval or circular in form.

"SPIKE KNOT. A spike knot is one sawn in a lengthwise direction; the mean average width shall be considered in measuring these knots.

"PITCH POCKETS. Pitch pockets are openings between the grain of the wood containing more or less pitch or bark. These shall be classified as *small, standard,* and *large* pitch pockets.

"(a) *Small Pitch Pocket.* A small pitch pocket is one not over ⅛ in. wide.

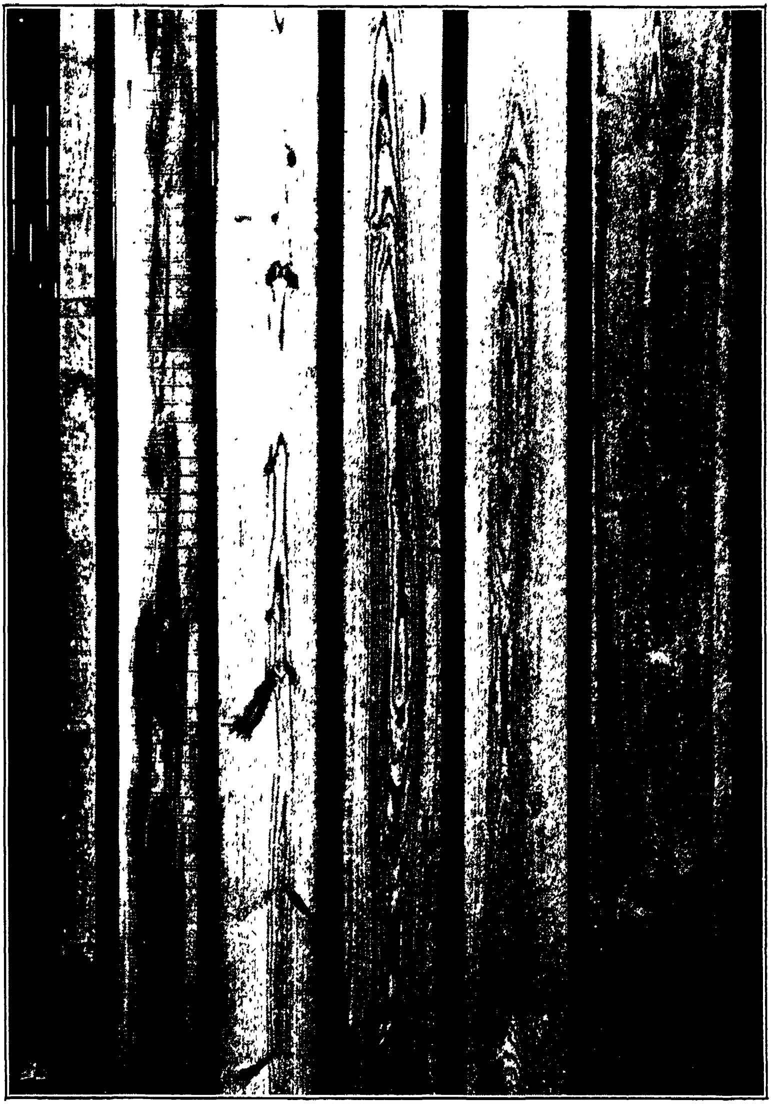
"(b) *Standard Pitch Pocket.* A standard pitch pocket is one not over ⅜ in. wide or over 3 in. in length.

"(c) *Large Pitch Pocket.* A large pitch pocket is one over ⅜ in. wide or over 3 in. long.

"PITCH STREAK. A pitch streak is a well-defined accumulation of pitch at one point in the piece. When not sufficient to develop a well-defined streak, or where the fibre between the grains, that is, the coarse-grained fibre, usually termed "spring wood," is not saturated with pitch, it shall not be considered a defect.

"WANE. Wane is bark, or lack of wood from any cause, on edges of timbers.

"SHAKES. Shakes are splits or checks in timbers which usually cause a separation of the wood between the annual rings.



(Courtesy of U. S. Forest Service)

LOW GRADE HIGH GRADE

Figure 30. Lumber Grades of Longleaf Pine

"ROT, DOTE AND RED HEART. Any form of decay which may be evident either as a dark red discoloration not found in the sound wood, or the presence of white or red rotten spots, shall be considered as a defect.

"RING SHAKE. An opening between the annual rings.

"THROUGH SHAKE. A shake which extends between the two faces of a timber."

Strength of Lumber.—Exhaustive tests of the strength of various species and grades of timber have been carried out by the U. S. Forest Service and are carefully recorded in their bulletins. (See Figure 30.) Furthermore, very complete tables of working stresses recommended by the Forest Products Laboratory, U. S. Forest Service, are included in the specifications of the American Society for Testing Materials. However, since this work is not intended for a reference book such tables are purposely omitted. It is thought advisable to give a

TABLE 1. SAFE WORKING STRESSES FOR STRUCTURAL TIMBER

(For green timber for bridges and trestles)

Increase 25% for highway bridges and still more for buildings and similar structures wherein timber is protected from weather and not subject to impact.

(All values in pounds per square inch)

Kind of Timber	Compression		Bending Extreme, Fibre	Shearing Along Grain
	Along Grain	Across Grain		
Douglas fir	1,200	310	1,200	170
Longleaf pine	1,300	260	1,300	180
Shortleaf pine	1,100	170	1,100	170
White pine	1,000	150	900	100
Spruce	1,100	180	1,000	150
Norway pine	800	150		
Tamarack	1,000	220	900	170
West hemlock	1,200	220	1,100	160
Redwood	900	150	900	80
Bald cypress	1,100	170	900	120
Red cedar	900	230	800	
White oak	1,300	450	1,100	210

brief table of comparative strength values and the following, which was adopted by the American Railway Engineering Association is believed to be adequate for a general idea of comparative strengths.

These values are in general somewhat higher than those recommended by the Forest Products Laboratory, especially in shear parallel to the grain.

Grading of Lumber.—The following paragraphs are extracted from those pages in the specifications of the A. S. T. M. explaining the background for derivation of the grading rules.

The purpose of the structural grades is to offer means for selecting structural material for strength, and uniformity in strength, in order that appropriate working stresses may be assigned for its use.

FACTORS OF STRENGTH. The most important factors which influence the strength of structural timber are the size, number, and location of defects, and the extent of exposure to moisture during use. These factors must all be considered in design or grading if the maximum utilization is to be obtained from the material used.

STRUCTURAL GRADES AND STRENGTH. Structural grades control defects by limiting their size and location in accordance with their effect on the strength. Working stresses for each species are recommended by the Forest Products Laboratory, U. S. Forest Service, and take into consideration the allowable defects, the moisture content as determined by use, and, in the case of southern pine and Douglas fir, rate of growth and percentage of summer wood.

MOISTURE. Moisture affects the strength of structural timbers both directly and indirectly. The direct effect of loss of moisture is the stiffening and strengthening of the wood fibres. This increase of strength, however, is accompanied by checking, splitting, warping, and twisting; as a consequence, some of the strength due to drying is lost. Timbers are also subject, during use, to varying conditions of moisture—from the dry location of a heated building to the continually wet conditions of some pier and dock timbers. All of these conditions are taken into account in recommending working stresses under different conditions of use.

Size Effects. In dimension material, 4 in. and less in thickness, the development of defects during seasoning does not offset the increase in strength from drying as much as in the larger sizes; and in these sizes used in dry locations, higher working stresses in the extreme fibre in bending can be recommended than in pieces of larger size having proportionately equivalent defects.

Defects. The principal defects which must be limited in structural grades are knots, shakes and checks, and angle of grain.

Influence of Knots. The influence of a knot is determined by its location in a piece and the area of its projection on the cross-section of the piece, the method of measurement being such as to give the best approximation of this influence. Knots in posts and heavy beams, which are likely to show only on one face or to run diagonally through the piece, reduce the strength in practically direct proportion to their size as measured. In dimension sizes, such as joist, in which the knot is likely to run directly through the piece, the strength is measured by the square of the effective depth, assuming the knot in its worst position, near the edge of the piece, and the reduction in strength due to the knot is approximately twice the ratio of the size of the knot to the width of the face. In similar material used flat, as plank, the influence of the knot is directly proportional to the size, as on the top and bottom edges of beams.

KNOTS AND HOLES. In grades for structural uses, no distinction is made between intergrown knots and encased knots or knotholes, observation at the Forest Products Laboratory in recent tests having shown that intergrown knots reduce the strength fully as much as encased knots or knotholes.

SHAKES AND CHECKS. Shakes reduce the area of a beam acting in resistance to shear, and the limitations placed on shakes are based on this reduction. Checks are limited on the same basis as shakes, and no combination of shakes and checks is permitted which would reduce strength to a greater extent than would the allowable size of either separately.

SLOPE OF GRAIN. Slope of grain, resulting either from diagonal sawing or from spiral or twisted grain in the log, is limited in accordance with the recommendations of the Forest Products Laboratory, based on the results of detailed study of the effect of cross and spiral grain upon strength and the weakening of material by checks which invariably develop and without exception follow the grain. There is not much reduction in strength from cross grain until an angle of grain of 1 in 40 is reached. From that value as a beginning, the strength decreases as the slope increases so that an angle of grain of 1 in 20 reduces the strength about one-eighth; 1 in 15, about one-quarter; 1 in 11, about three-eighths; and 1 in 8, about one-half. In a post or column an angle of grain of 1 in 15 reduces the strength about one-eighth; 1 in 11, about one-quarter; 1 in 8, about three-eighths; and 1 in 6, about one-half. These are of course average values only.

WANE. Wane is limited by such consideration as bearing area, nailing edge, appearance, etc., rather than by effect on strength, although no combination of wane and knots which would reduce the strength more than the maximum allowable knot will be allowed.

PITCH POCKETS. Pitch pockets are ordinarily not defects in a structural grade. A large number, however, indicates a general lack of bond, and such a piece should be carefully inspected for shakes.

HEARTWOOD AND SAPWOOD. Heartwood and sapwood have been found by the Forest Products Laboratory to be of equal strength, and no requirement of heartwood need be made when strength alone is the governing factor. Heart requirement, when durability of untreated material under exposure is a factor, as in bridges, trestles, docks, and piers, or in damp buildings, or buildings in which conditions of high humidity prevail, may be specified in any grade, according to exposure and use. When preservative treatment is to be applied, there should be no restriction as to sapwood, as sapwood is easier to treat than heartwood and a large amount is to be preferred.

DENSITY AND STRENGTH. The density of the wood substance of all species is practically the same. The dry weight is, therefore, a measure of the amount of wood substance present; and on the amount of wood substance present depends the strength of the clear wood. No pieces of exceptionally light weight are permitted in the select grades, but light weight pieces otherwise of select grade may be accepted in the common grades.

DENSITY AND SUMMER WOOD. In southern pine and Douglas fir, the proportion of summer wood, the dark portion of the annual rings, furnishes a practical means of estimating the density. Selection of these species for density, to the extent that dense material is commercially available, assures material of the highest character from the standpoint of strength and uniformity in strength, in the clear wood.

CONTRAST BETWEEN SUMMER WOOD AND SPRING WOOD. In acceptance for density the contrast in color between summer wood and spring wood should be distinct. Absence of contrast occasionally occurs in bands of growth rings which appear on the whole darker than the adjacent material. The summer wood merges into the spring wood abnormally with a gradual change of color, leaving practically no material which has the normal appearance of spring wood. Such material has been called by a number of names, including proud wood, red wood, and compression wood. It has a decided end shrinkage, is weak in tension and even a small part of a cross-section of this character makes it undesirable in high-class structural timbers.

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Proceedings of the A. S. T. M.

CHAPTER 3

LIME AND PLASTER

Lime or "quicklime," as it is generally called, is the product resulting from the "burning" of limestone. The heat of the burning process drives off carbon dioxide leaving the oxide which constitutes the "lime."

High Calcium Lime.—This material is a lime that contains at least 90% of calcium oxide.

Magnesian limes contain 10% to 40% of magnesium carbonate.

Dolomitic limes contain over 40% of magnesium carbonate.

Slaking.—When water is added to quicklime the mixture expands with the evolution of considerable heat, and forms hydrate of lime. This hydration process is commonly called "slaking."

Yield.—The volume of lime paste of a definite consistency which a given amount of lime will produce is known as the *yield.* This is important, because it indicates the amount of lime required to produce a given amount of plaster or mortar. Limes that expand greatly and give a high yield are called "fat" limes, and those which give a low yield are called "lean" limes.

Sand-Carrying Capacity.—The sand-carrying capacity of a lime is closely related to the yield. It refers to the amount of sand which may be added to the lime paste, per barrel of lime, without rendering it too stiff for use.

Plasticity.—Plasticity, which ordinarily is understood to mean "capacity for being molded," when used with reference to mortar and plaster, refers to the spreading quality of the material as used under the trowel. If it spreads smoothly and with comparative ease it is called plastic; if it drags under the trowel, or cracks, curls and drops as the trowel passes, it is not plastic and commonly called "short."

High Calcium Limes.—High calcium limes expand greatly on slaking, producing a large yield and therefore have a high sand-carrying capacity. The slaking takes place very rapidly and therefore the temperature is liable to rise to a dangerous degree and burning is liable to occur unless considerable care is used. Mortars made from high calcium limes are apt to be "short" or non-plastic.

Dolomitic Limes.—Dolomitic limes slake slowly with much less heat than high calcium limes; there is little danger of burning during the slaking process; they expand less, i.e., have a much smaller yield; they are much more plastic. Owing to the smaller yield the sand-carrying capacity would seem to be low, but owing to the high plasticity the sand-carrying capacity would be raised.

Magnesian Limes.—Magnesian limes would range in between the two described above, but as a matter of fact most limes are either very low or very high in magnesia and the so-called magnesian limes are of minor importance.

Various impure limes, rather dark in color and of general inferior quality, appear on the market. They slake slowly; have a low yield and poorer mechanical qualities.

Contractors often prefer high calcium lime on account of the large mortar yield, but masons much prefer to work the dolomitic limes because they are so much more plastic. Tests have shown that after a considerable time, the dolomitic lime mortars are much stronger than the high calcium lime mortars, although the early strength of dolomitic lime is low.

Lime Mortar and Plaster.—Lime paste alone cannot be used for mortar as it would shrink and crack, besides being too expensive. Therefore it is necessary to add at least 2 to 4 parts of sand.

Lime intended for mortar is usually slaked in a mortar mixing box and when sufficiently worked and a putty or paste of the proper consistency is formed it is covered with sand to protect it from the air. As it is needed it is gradually mixed with the proper proportion of sand until the whole is used up.

Lime intended for use as plaster was formerly slaked and placed in barrels with a little excess water over the surface to protect it from the air. It was stored in this manner for several weeks, or sometimes even months, to insure proper seasoning. It was then mixed with the proper amount of cattle hair, or other fibre, and sand, to be used for plaster.

The present practice is to slake the lime in a box and as soon as the paste is formed add the hair and some sand to form the plaster stock. The material thus made is thrown from the mixing box to a prepared bed and more mixed until enough stock for the "job" is on hand. This is allowed to stand for from a few hours to two or three weeks. If used too soon there is a great danger that it will not be properly tempered and small blisters known as "limepops" are apt to appear on the finished wall. If allowed to stand too long the lime will "eat out" the hair and there will be no fibre to give the plaster strength, and trouble will arise from that source. The present practice is much inferior to the older methods.

Hardening of Lime.—Lime hardens by a simple chemical process, but it is well to understand exactly the nature of that process.

The carbon dioxide of the air unites with the lime to form limestone. $CaCO_3$ from which the original quicklime was formed. However, the CO_2 of the air will not unite with dry lime hydrate directly, for excess water must be present to form with the CO_2 the equivalent of carbonic acid, H_2CO_3, and then the reaction takes place as follows:

$$H_2O + CO_2 + CaO_2H_2 = CaCO_3 + 2\ H_2O$$

This shows why it is necessary to prevent quicklime plaster from drying too quickly, and also how the hardening proceeds slowly for a long time. It also shows why a freshly lime plastered wall should not be painted if it is expected to develop any great hardness and strength in a reasonable time.

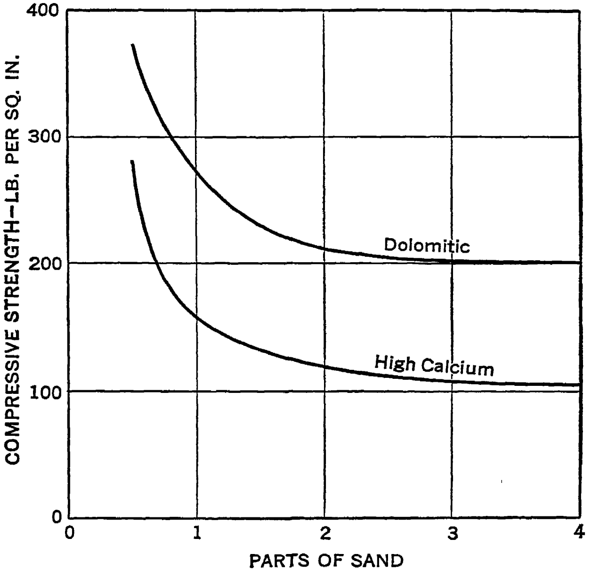

Figure 31. Relation Between Sand Content and Compressive Strength of Lime Mortar—Results at Age of 90 days (From tests by Emley and Young)

Figures 31 and 32, prepared from results reported by Emley and Young, show the comparative strength of dolomitic and high calcium limes, as well as the effect of size of sand particles, and proportions of sand to lime paste. Results are at 90 days.

It is easily seen that the dolomitic limes are considerably stronger than the high calcium limes, and that fine sand produces much better results than the coarser material.

Besides its use for ordinary lime mortar and building plaster, lime is used to increase the plasticity of Portland cement mortar, for stucco, and to aid in waterproofing Portland cement concrete.

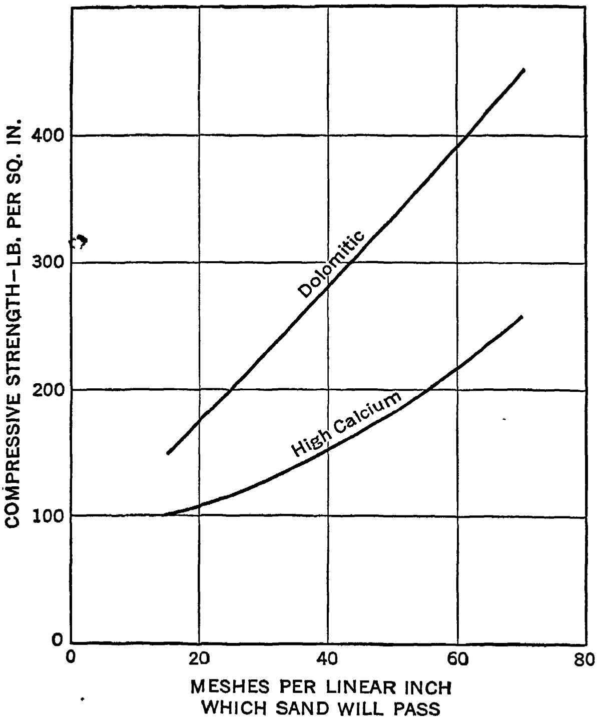

Figure 32. Relation Between Size of Sand Grains and Compressive Strength of 1/3½ Sand-Lime Mortar—Results at Age of 90 Days (From tests by Emley and Young)

Air-Slaked Lime.—When quicklime is exposed to the air, it absorbs moisture and expands so that the lumps fall into a fine powder. Immediately this material absorbs carbon dioxide from the atmosphere and so becomes simply powdered calcium carbonate ($CaCO_3$). It is thus seen that the term "air-slaked" is very misleading, for the resulting powder is completely ruined as a cementing material. If lime is so packed or confined that it will not fall away as it becomes air-slaked, a surface coating is formed that prohibits the further penetration of moisture and carbon dioxide. In such a case the air-slaked covering acts as a protective layer, preventing the spoilage of the material underneath.

Hydrated Lime.—Hydrated lime is lime that has been chemically satisfied with water, to form a dry, flocculent powder. In order to accomplish this it is necessary that lump quicklime be ground to a fairly uniform small size, after which it must be thoroughly mixed with sufficient water (but not an excess), and finally it must be reduced to a fine, uniform powder.

Builders and contractors have been slow to take up the use of this material because of their distrust of material which has been "air-slaked." This objection is being overcome, however, in favor of a more extended use of the hydrated material.

It would seem as if hydrated lime and ordinary slaked quicklime should be exactly alike, since they are chemically the same product, but the fact is that mortars made from hydrated limes are much stronger than those made from the putty produced by slaking quicklime. Some advantage is experienced in the ease with which mortar may be produced by the use of physically dry hydrated lime which may be mixed dry with the sand to produce a more perfect blend, but mortars made from hydrated lime are notoriously "short," non-plastic, and hard to work. The yield is small.

Hydrated lime does not deteriorate much in shipment and is considered safe to ship even by water, whereas quicklime is considered as a great hazard to ship by water on account of the expansion and heat which are produced if it gets wet.

"Alca" hydrated lime is a high alumina lime and is much more plastic than the ordinary variety. Masons find it only excelled in this capacity by well-seasoned lump lime plasters.

Hydraulic Lime.—Hydraulic lime is formed by the burning of impure limestone containing considerable silica and alumina.

Ordinary lime will slake but will not set and harden under water; hydraulic lime will not only slake so as not to require grinding after burning, but will also set and harden under water.

Before Portland cement was available under such favorable conditions as at present, hydraulic lime had quite a commercial importance, especially in Europe, where the industry still flourishes to a certain extent. In the United States no attempt has been made to develop the industry, mainly because of the abundance of material available for natural and Portland cements, with which hydraulic lime cannot compete as a structural material.

Some hydraulic lime and *grappier cement,* which is made by grinding the lumps or grappiers left after slaking the hydraulic lime, are used for architectural decoration on account of their light color and non-staining characteristics. These materials are mostly imported from Europe.

Gypsum Plasters

Pure, crude gypsum is a hydrous sulphate of lime. In its natural form the chemical composition of the crystals is represented by the formula $CaSO_4 + 2\ H_2O$. That is, each molecule of calcium sulphate is combined with two molecules of water.

Gypsum plasters are formed primarily by either partial or complete dehydration of the crude gypsum. Certain other materials to act as retarders or accelerators of set, or to modify the plasticity, may or may not be added during or subsequent to calcination.

Plasters Produced by Incomplete Dehydration.—If crude gypsum is heated to between 212° F. and less than 400° F. three-fourths of the water of crystallization will be driven off, so that the chemical composition will then be $CaSO_4 + \frac{1}{2}H_2O$. Plasters produced in this way are plaster of Paris, or cement plaster, according as they are quick setting or slow setting.

Plaster of Paris is produced by the partial dehydration of a *pure gypsum,* without the addition of foreign materials, either during or after calcination. When the material is finely ground and water added, it very quickly reabsorbs water enough to regain its original composition of $CaSO_4 + 2\ H_2O$ and quickly sets into a hard rock-like mass in a few minutes.

Cement plaster is produced by the partial dehydration of an *impure* gypsum, or else by the addition to plaster of Paris of certain materials which serve to retard the set.

These plasters are often loosely called *calcined* plasters, in the trade.

Gypsum stucco is practically the same as plaster of Paris. The only difference is that stucco is apt to be a little dark in color, where plaster of Paris is white; and stucco is not quite so finely ground. Both are made from pure gypsum and neither has any retarder.

Wall plaster is made by adding hair or some other fibre to cement plaster.

Plasters Produced by Complete Dehydration.—If crude gypsum is heated to above 400° F. it loses all of its water of crystallization and becomes much slower setting, but unless heated too high or too long, it still retains the power to reabsorb its water of crystallization and harden into a rock-like mass.

Plasters produced in this way are flooring plaster and hard finish plaster.

Flooring plaster is produced by the complete dehydration of a pure gypsum.

Hard finish plaster is produced by the complete dehydration at a red heat or over, of a gypsum to which alum or borax or some such substance has been added. Keene's cement is of this latter variety, containing alum, and Macks' cement another containing burnt Glauber's salts, Na_2SO_4, or potassium sulphate, K_2SO_4.

Strength of Gypsum Plasters.—The tensile strength of neat gypsum plasters is from 400 to 500 lb. per sq. in. at the end of a year. Plaster of Paris has a high early strength and a maximum at about three months, when it may go up as high as 650 lb. per sq. in., but it shows considerable retrogression thereafter.

The impure and hard-burned plasters do not gain as rapidly in strength, but they do not show so much retrogression, and the Keene's cement shows no retrogression. The compressive strength of neat plasters often goes as high as 2,500 lb. per sq. in., and rapidly decreases with increase in volume of mixing water. Retarders decrease the strength to a marked degree.

Gypsum plasters should *not* be kept wet after setting if they are to harden properly.

Structural Uses of Various Gypsum Plasters.—Plaster of Paris sets very rapidly and expands slightly as it sets. For this reason it is fitted for various special uses as a casting plaster, but is very little used as a material of engineering construction. As already stated, a coarsely ground, dull colored material sometimes called "stucco" is used for interiors and certain molded ornaments. "Stucco," as defined by the A. S. T. M., is a material used in the plastic state, which can be trowled, to form a hard covering for *exterior* walls or other *exterior* surfaces of any building or structure. Stucco generally used for exterior is either a Portland cement or a Portland cement mixed with some lime or magnesia.

Cement or hard wall plasters mixed with hair or fibre and hydrated lime or clay are used as wall plasters with certain advantages, especially when it is desired to paint the surfaces soon after they are set.

Gypsum plasters will not carry as much sand as lime plasters and are harder to work and so are more expensive. They are more fire-resistant than lime plasters and they are less susceptible to expansion and contraction, and consequent cracking. Lime manufacturers make equally important counter claims but the advantage of each depends upon the class of work upon which it is to be used.

Gypsum Plaster Products.—Gypsum plaster products are becoming quite universally used in building constructions of various kinds. They set and harden very rapidly and so allow construction to proceed without delay, and besides that they are highly fire-resistant. It is largely this property of high resistance to fire which has led to their widespread use. Gypsum building products are produced as gypsum plaster board, gypsum wall board, and gypsum tile or block.

Gypsum wall board is made in sheets or slabs, generally ⅜ in. thick, having an incombustible core of gypsum with or without fibre intimately mixed, not in excess of 7% or 8%, with a paper or fibre surface firmly bonded to the core. It is intended for use without addition of plaster for the purpose of furnishing a surface which may receive decorations directly. It may be obtained in sheets from 6 to 10 ft. long and in widths of 32 and 48 in.

Gypsum plaster board is similar to wall board except that it has a surface which is intended for subsequent plastering. One style used as lath is 16 in. by 32 in., or 16 in. by 48 in., by ⅜ in. thick. Another kind comes in sheets 32 in. wide, 8 ft. long, and ½ in. thick. These lath or backing boards make a hard, stiff, vermin proof wall, highly resistant to fire. The surfaces are specially prepared to take gypsum plaster as a finish.

Gypsum tile are classed as partition tile, furring tile, roof tile and floor void tile. "Pyrobar" tile as made by the United States Gypsum Co., is 97% gypsum and 3% special wood fibre. These tile are 30 in. long, 12 in. high, and of various thicknesses from 1½ in. to 6 in. (solid or hollow).

Uses of Gypsum Tile.—The uses of this type of gypsum tile for fireproof construction are listed as follows:

1. Non-bearing corridor walls, partitions, wall furring, and false columns and pilasters, partitions and corridors in merchandise storage warehouses.
2. Fire division walls.
3. Elevator, stairway, dumbwaiter, and corridor enclosure.
4. Lightwells, pipe chases, heat and vent ducts.
5. Coverings for columns, beams, girders, trusses, and other steel members requiring fireproofing.
6. Floor fill in place of cinder concrete.
7. Insulation on concrete roof.

A special shape of tile is made for roof construction and another for floor construction. All these gypsum products act as effective sound deadeners.

Gypsum Plaster Concrete.—Another gypsum product developed for fireproof construction, is a gypsum plaster concrete made from a specially prepared gypsum plaster of high strength which may be mixed with steam coal cinders, blast furnace slag, crushed stone, or gravel. The form made by the United States Gypsum Co. called "Structolite," when mixed neat, is said to possess a strength of 2,500 to 3,000 lb. per sq. in. and concrete of the proportions of 1½ parts Structolite, 1 part sand, 3 parts coarse aggregate, shows a strength of 900 to 1,300 lb. per sq. in. This material generates some heat while setting, and as it sets so that forms may be removed in less than one-half hour it has advantages for work in cold weather.

Explicit directions for the use of these materials may be obtained from the manufacturers. Large quantities of these materials are being used in important construction, such as public buildings, manufacturing plants, schools, hospitals, hotels, apartment buildings, residences and churches.

Reference

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CHAPTER 4

HYDRAULIC CEMENTS AND CONCRETES

Definition.—Hydraulic cements may be defined as those which will set and harden under water. Those of any consequence classify as follows:

Natural Cement
Puzzolan Cement
Slag Cement
Portland Cement
Tufa Cement
Improved Cement
High Alumina Cement

Portland Cement.—The definition from the specifications of the A. S. T. M. is:

"Portland Cement is the product obtained by finely pulverizing clinker produced by calcining to incipient fusion, an intimate and properly proportioned mixture of argillaceous and calcaceous materials, with no additions subsequent to calcination excepting water and calcined or uncalcined gypsum."

In the first place Portland cement is an *artificial* mixture of ground lime rock, or equivalent, and clayey material, in very definite and carefully controlled proportion. This artificial mixing and control insures uniformity of ingredients. Calcining to a certain physical state insures uniformity in burning, and very fine grinding, after calcination, secures an active and uniform material of exceptionally good hydraulic properties. The gypsum is added as a control for the time of set.

Portland cement is one of the most important materials of construction and its properties will be discussed at length on subsequent pages. Slag Portland cement is a true Portland cement and should not be confused with slag puzzolan cement.

Natural Cement.—Natural cement is made by burning a material known as "cement rock." This rock is a natural material, largely limestone, but with a considerable amount of clayey substance throughout.

Cement rock varies considerably in its composition and the temperature of burning is not closely controlled so that natural cement is not a uniform product. The clinker from some cement rock has sufficient free lime to slake slowly, but in general this action would be very slow and grinding is necessary for development of hydraulic properties.

Natural cement varies from yellow to brown in color and has a specific gravity of 2.80 to 3.00.

Natural cements set rather rapidly; in general about three times as fast as Portland cement. The strength is quite variable but not much over half that of Portland cement.

Natural cement has been used in sewer work and in monolithic, or massive, construction where great strength is not required, but its variability in strength and the greater economy offered by the use of Portland cement have resulted in its nearly total disappearance from the market.

Puzzolan Cement.—Puzzolan cement is made by grinding together a natural volcanic ash called "puzzolana," with hydrated lime, in the proportion of two parts of puzzolana to one part of hydrated lime. There is no calcination of this product; the materials are simply ground and mixed. It is not a Portland cement in any sense.

Besides puzzolana, granulated slag may be used. When slag is used the resulting cement is called "slag cement." This is the only puzzolan cement produced in the United States. It should be carefully distinguished from slag Portland cement, however, which is a different material.

Slag puzzolan cement sets about as rapidly as Portland cement, but hardens much more slowly.

Tufa Cement.—Tufa cement is a blended cement in which one of the constituents is Portland cement and the other a partially consolidated pumiceous rock of volcanic origin called tufa. Tufa contains more or less soluble silica which probably reacts with the lime in the cement which exists as uncombined calcium hydroxide. In Portland cement this excess hydroxide would ultimately crystallize and harden, but when ground with the tufa it forms a colloidal calcium hydro-silicate, which is the chief component in the hardening of cement. The very fine grinding of blended cements probably promotes this reaction to a large degree. A product of 50% Portland cement and 50% tufa, ground to a fineness such that 90% would pass through a 200 mesh screen, produced a blend which was practically equal in strength to the original Portland cement. It passed the standard specifications for Portland cement but was somewhat slow in hardening.

Sand Cements.—Sand cements have been used in some inaccessible places with considerable success. Sand cements are blended cements very similar to tufa cement. They are generally made by grinding together siliceous sand and Portland cement. Quartz is not desirable because it contains little soluble silica, but basalts and sandstones have been successfully used. Here again strength is maintained on account of increased activity of a chemical nature partly due to the satisfying of the excess calcium hydroxide and partly to the extra fine grinding.

Improved Cements.—Improved cements are improved only in relation to natural cement, which is their basis. Some manufacturers have sought to improve the properties of natural cement by grinding some Portland cement clinker with the natural cement clinker. There is very little of this material on the market at the present time.

High Alumina Cement.—High alumina cement is a hydraulic cement which has been used in France for some time, but which has only lately appeared in American markets. It is made from limestone and bauxite; sometimes by the dry process for Portland cement or by fusion in the electric furnace.

Initial set takes place a bit more slowly than in the case of Portland cement, but in concretes and mortars of the usual proportions it attains a strength in 24 hours equal to that of Portland cement concretes at the end of several months.

High aluminate cements are somewhat dangerous to use under certain circumstances, especially when mixed with other cements. Under such circumstances what is known as "flash set" may occur, with the result that it will set before it is possible to place it.

Reports of failure of road pavement of this material on cross-road locations where it was necessary to let traffic pass as soon as possible have been noted. The rest of the road surface of ordinary Portland cement concrete has been reported as standing up perfectly well.

This cement contains about four times as much alumina as Portland cement, about 2/3 as much lime, five times as much iron oxide, and very little silica, as against some 22% in Portland cement.

The cost of this kind of cement is about four times that of Portland cement on account of the high cost of the raw material bauxite, which is also the source of the metal aluminum.

Besides the advantage of high early strength it is claimed that high alumina cement has superior resistance to sea water and water containing soluble sulphates.

Properties of Portland Cement.—Of all the hydraulic cements Portland cement is the most important, and properties of others are compared with those of Portland cement as a measure of their worth. Accordingly, the specifications for physical properties of Portland cement will be explained and discussed at some length, and no detailed account of the properties of the less important cements will be included in this elementary survey.

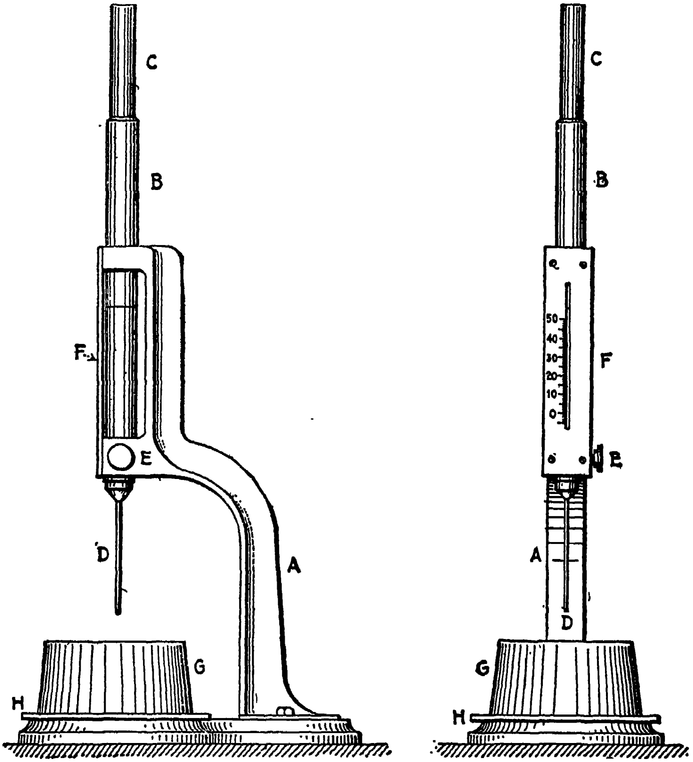


Figure 33. Vicat Apparatus

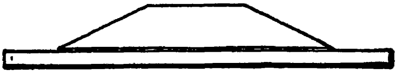
The definition for Portland cement has been given in a previous paragraph.

The specifications for physical properties are as follows:

Fineness. The residue on a standard No. 200 sieve shall not exceed 22% by weight.

Soundness. A pat of neat cement shall remain firm and hard, and show no signs of distortion, cracking, checking, or disintegration in the steam test for soundness.

Time of Setting. The cement shall not develop initial set in less than 45 minutes when the Vicat needle is used or 60 minutes when the Gillmore needle is used. Final set shall be attained within ten hours. (See Figures 33 and 34).



Pat with Top Surface Flattened for Determining Time of Setting by Gillmore Method

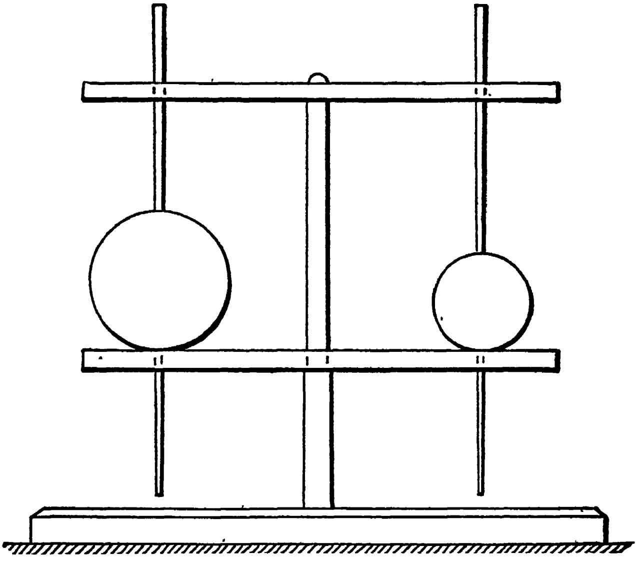


Figure 34. Gillmore Needles

Tensile Strength.—The average tensile strength in pounds per square inch of not less than three standard mortar briquets, composed of one part cement and three parts of standard sand, by weight, shall be equal to or higher than the following:

Age at Test days	Storage of Briquets	Tensile Strength lb. per sq. in.
7	1 day in moist air, 6 days in water	225
28	1 day in moist air, 27 days in water	325

The average tensile strength of standard mortar at 28 days shall be higher than the strength at 7 days.

Standard specifications require 94 lb. of cement net, to the bag and 276 lb. net, to the barrel.

Discussion of Specifications.—Fineness of grinding has a marked effect upon the strength of the mortar produced from a given cement. Coarse particles are not active and act about as so much sand, so that in general the finer the grinding the higher the strength of the mortar.

It is very necessary to realize that this increase of strength refers to mortar and not to samples made entirely of cement with no sand (called *neat* cement samples).

Briquets made of neat cement often show a decrease in strength as the fineness increases, although experiments have shown that this is not always true.

At any rate there is no question about the effect of fineness upon the strength of mortars, and many cements are ground today so that about 90% will pass through the No. 200 sieve. These finely ground cements are not only stronger than the coarser ones but they gain strength more rapidly.

Soundness is very important, for if cement begins to disintegrate after setting, it is ruined. Unsoundness is generally ascribed to the action of free lime, which does not become hydrated until after the cement has acquired its set in the process of hardening. When such lime finally begins to react with water, it does so with sufficient violence to cause the cement to crack or disintegrate. Fine grinding is generally sufficient to expose any free lime to such an extent that it will become hydrated before setting is completed, for it is supposed that only the coarser particles would be slow enough in reaction to be dangerous.

Time of Set.—The word "set" as used in the making of cement mortars and cements refers to the formation of the crystalline network which binds the particles of the mass together.

For convenience, this idea of set has been divided into two conceptions, viz.: *Initial set* is said to have occurred when the *initial plasticity disappears slightly* and the material becomes capable of withstanding an arbitrarily defined, but very light pressure. This is the beginning of the process of crystallization. When this first process of formation of the crystallization network is complete and the plasticity has disappeared entirely and the sample become stiff and hard, *final set* is said to have taken place. Final set is determined arbitrarily by noting the elapsed time necessary for the sample to reach a stage where it will withstand a very much greater arbitrary pressure.

There are two commonly used methods for determining the time of set, as has been indicated already.

Time of set by the Vicat needle method is determined by noting the penetration of a needle 1 mm. in diameter, loaded to weigh 300 grams, into a mass of cement paste retained in a standard ring container. The ring is in the form of a hollow frustum of a cone 7 cm. in diameter and 4 cm. high. When the needle ceases to pass a point 5 mm. above the plate in ½ minute after being released in contact with the paste at the top, initial set is said to have taken place. When the needle ceases to penetrate appreciably, final set is said to have taken place.

The Gillmore needles for time of set consist of two flat-ended needles. One has a flat end 1/12 in. in diameter and is loaded to weigh ¼ lb. The other has a flat end of 1/24 in. in diameter and is loaded to weigh 1 lb.

A pat of neat cement paste of normal consistency is made about 3 in. in diameter and ½ in. thick. The time of initial set is noted when the ¼-lb. needle will cease to make any appreciable indentation. The time of final set is noted when the 1-lb. needle will cease to make any appreciable indentation.

It should be noted that the pressure of the large needle is 16 times that of the small needle.

Normal Consistency.—The amount of water used in gauging cements has a great influence upon the time of set, as well as in the final strength attained, and for this reason, if for no other, a standard amount of water for any given cement must be used to produce the paste or mortar to be used in testing.

The most satisfactory scheme for determining this standard amount of water is to measure it in reference to the plastic consistency of the paste it produces. The proper consistency for this standard is called the *normal consistency.*

In the determination of the normal consistency the Vicat apparatus is generally used, but in this case instead of the 1 mm. needle being used, the rod is reversed and the plunger 10 mm. in diameter is used.

An amount of 500 grams of cement is gauged with water and mixed, squeezed, and kneaded very vigorously with the hands for at least one minute, and until it does not get any wetter, and a ball is then formed and forced into the conical ring of the Vicat apparatus. After the excess paste has been sliced off from the top of the ring, the ring full of paste is put under the plunger, which is released in contact with the paste. When the rod penetrates the paste exactly 10 mm. below the original surface in ½ minute, normal consistency is attained.

The normal consistency of a standard sand mortar is based on the normal consistency of the paste made of the cement to be used. Having determined the normal consistency of the paste, the necessary percentage of water for the normal consistency of the standard sand mortar is arbitrarily set, and is determined by reference to a table giving percentages of water for normal consistency of paste and corresponding percentages of water for the standard sand mortars.

"Standard sand" is a clean, smooth or round, white, quartz sand, which comes from Ottawa, Ill., and is sometimes called "Ottawa Sand." The material actually used is that which will pass a 20 mesh sieve, but which will be retained on a 30 mesh. Mortars made from this sand are called standard mortars; and since the sand is a constant, variation is due to cement, and hence the use of this material for testing of cement.

The normal consistency of a bank sand mortar is determined only by comparison with standard mortars. The amount of water necessary to produce a mortar consistency about as wet as that of the standard mortar has sometimes been taken as the proper amount to use for comparative purposes. However, the most modern methods of mixing mortars have made other provisions for determining the proper amount of water to be used, and this will be discussed at greater length in succeeding pages.

Tensile Strength.—Although cement is not used where any dependence has to be placed upon the tensile strength, the tensile strength tests of standard mortar briquets are the best criterion of the quality of cement. Tension tests of mortar briquets also afford a rough index of the quality of concrete which may be made from the cement. However, this latter index is unreliable and has been largely discarded in favor of special compression tests on small mortar specimens, mainly cylinders 2 in. in diameter and 4 in. high.

It is very necessary that all such samples shall be stored under water, according to specifications.

Making of Mortar and Concrete.—Concrete and mortar in construction require quite a different kind of consideration from that given to most other materials, because they are made and placed under conditions which may be extremely variable and unless great care is used a uniformly satisfactory product will not result.

Constant check-up must be made upon the quality of cement, fine and coarse aggregate, and upon the proportions and mixing of these ingredients, as well as upon the amount of water used to gauge the entire mass. In important work frequent test-cylinders of the material, as placed, are made and sent to commercial laboratories, as a check on the quality of the concrete entering the structure. Formerly, specifications simply referred to more or less easily determined properties of the raw materials, and have stated certain arbitrary proportions; and in some cases have stated a method required for mixing. However, this was unsatisfactory in many ways, and therefore recently there has been a great change in specifications which now omit any reference to the raw materials or the method of mixing, but simply state that the resulting product must have a certain stated strength at the 28-day period, as indicated by compression tests made on 6-in. diameter cylinders 12 in. long, molded from the material as placed. Research by the Portland Cement Association and resulting methods of computation of required proportions of raw materials have made it possible to meet such specifications with surprising accuracy.

Mortar.—Mortar is a mixture of cement and sand, or screenings, or similar material, and water, which has the capacity for hardening into a rock-like mass. The size of the coarsest particles of the inert materials, in general, does not exceed that which would pass a ¼ in. mesh sieve.

Concrete.—Concrete is a mixture of mortar and gravel or crushed rock, or similar material. The coarse material for ordinary concrete seldom exceeds 2 in., but rubble concrete is made by using large boulders or broken rocks within the mass of ordinary concrete. This rubble concrete is often called "Cyclopean Concrete"; it is used in massive monolithic structures, such as dams and heavy walls. The large rocks simply fill up space and save a tremendous amount of cement which would otherwise be necessary.

Aggregate.—The inert particles in general are called aggregate. Aggregate may be sand, gravel, crushed rock, mine tailings, cinders, broken slag, or any such materials. The particles below ¼ in. in size are called fine aggregate, and those from ¼ in. to 2 or 3 in. are called coarse aggregate.

Unit Weight of Aggregate.—The unit weight of an aggregate is the weight per cubic foot of the material when carefully compacted in a standard measure by specified operations. The exact procedure for doing this is unimportant here but may easily be found by reference to the standard specifications of the American Society for Testing Materials.

Apparent Specific Gravity.—The apparent specific gravity of an aggregate is determined by experiment, based on the following equation:

$$\text{Apparent Specific Gravity} = \frac{\text{Weight of Dry Sample in Air}}{\text{Loss of Weight When Immersed in Water}}$$

This formula is a slight approximation but gives substantially correct results for all practical purposes.

Voids.—The voids in an aggregate are the vacant spaces between the particles of the aggregate. Since for the maximum strength of mortar or concrete it is necessary to get the maximum bond between particles, it is necessary to consider the vacant space to be filled with cement, or in other words, to determine the percentage of voids.

There are several ways of determining voids in aggregate. The direct method consists of pouring water into a receptacle already filled with a measured amount of aggregate. The water will penetrate the vacant spaces and finally show at the surface. The ratio between the volume of the water necessary to fill the voids and the gross volume of the aggregate, multiplied by 100, will give the percentage of voids more or less approximately. The error occurring in this method is largely on account of entrapped air which it is impossible to drive out. This causes an error such that the apparent percentage is less than the actual percentage.

A somewhat more accurate method is by comparison of the gross volume of the aggregate with the net volume as determined by the displacement method wherein a known gross volume is poured slowly into a measured volume of water and the volume of water displaced is noted.

The method of the A. S. T. M. is as follows:

$$\text{Percentage of Voids} = \frac{(\text{Specific Gravity} \times 62.355) - \text{Weight}}{\text{Specific Gravity} \times 62.355} \times 100$$

Here, specific gravity refers to apparent specific gravity as described above, and weight refers to unit weight, also described above.

Silt.—Silt is the very fine dust which is present in nearly all aggregates. The amount of silt which may be present without harm depends upon its nature. Too much silt in the form of clay is deleterious, as is also mica. If the silt contains more than about 10% of organic material there is a very noticeable effect upon the time of set and strength.

Organic Impurities.—Organic impurities increase the time of set and decrease the strength of Portland cement mortars. In bad cases, the set is entirely stopped and mortar, even at the end of a month, has practically no strength at all.

The method of test for organic impurities in sand (revised method of A. S. T. M., 1927) is about as follows:

A sample of about 1 lb. of the sand to be tested is carefully selected. From this sample a 12-oz. graduated clear glass bottle is filled to the 4½-oz. mark and then a 3% solution of sodium hydroxide in water is poured in until the liquid and sand together fill the bottle to the 7-oz. mark, after shaking. The bottle is stoppered and shaken vigorously, and then allowed to stand for 24 hours. A standard color solution is prepared by adding 2.5 c.c. of a 2% solution of tannic acid in 10%

alcohol to 97.5 c.c. of a 3% sodium hydroxide solution. This is shaken vigorously in a 12-oz. clear glass bottle and allowed to stand for 24 hours. After the required 24 hours have elapsed, the clear liquids above the test solution and above the standard solution are compared for color. The standard indicates 250 parts of organic material per million in terms of tannic acid.

The principal value of this test is a warning that other physical tests, such as time of set and strength, should be carried out before aggregates with a high "color value" are approved for use.

Sieve Analysis of Aggregates for Concrete.—Various methods for proportioning concrete mixtures depend upon the grading of sizes of the particles of the aggregate. This grading of sizes is determined by what is called the sieve or screen analysis.

Samples are obtained in the customary way by means of quartering, or by a sample splitter. The amount of the sample for sands is usually 500 grams, but for coarse aggregates it is taken as a weight in grams equal to 3,000 times the size of the largest sieve required, measured in inches.

The requirements for sieve sizes are briefly as follows:

Sieve Number	Size of Opening in Inches
No. 100	0.0058
No. 48	.0116
No. 28	.0232
No. 14	.046
No. 8	.093
No. 4	.185
3/8 in.	3/8
3/4 in.	3/4
1 in.	1
1½ in.	1½
2 in.	2
3 in.	3

It should be noted that up to and including the 3/4-in. screen, each sieve is approximately twice the linear size of the one preceding. Material is placed on the coarsest sieve first and sieving is continued until not more than 1% passes any sieve during one minute. The percentage by weight of the total sample, which is finer or coarser than each of the sieves, is computed.

Principles of Proportioning Materials in Concrete.—There have been a great many experiments made on various schemes for the proportioning of the materials, some of which have been abandoned. Others, however, have been used with considerable success, particularly where the conditions did not vary too much.

The present practice is based on the best points of several of the newer theories, and the following paragraphs will attempt to point out the important features of the individual theories, and the parts which are used in the modern method of proportioning. Finally the outline of the method of proportioning will be given, and also a method of computing the amounts of the different materials of the aggregate.

Proportioning of concrete ingredients was at first merely a matter of experience, and arbitrarily selected proportions of certain amounts were found to give fairly satisfactory workability and strength for certain types of work.

Some of the commonly used proportions for various classes of work, known to be fairly satisfactory are:

Reinforced concrete, average	1 : 2 : 4	or 1 : 2½ : 4	(For general strength)
Massive concrete	1 : 3 : 5	or 1 : 3 : 6	(Where strength is secondary)
Concrete roads	1 : 2 : 3	or 1 : 2 : 3½	(For strength and toughness)
Pavement bases and foundations	1 : 2½ : 4	or 1 : 3 : 5	(Fair strength)

Here the first figure is proportion of cement, the second refers to fine aggregate, and the third to coarse aggregate.

With the increase of the use of reinforced concrete and the desire for rational design and economy, it became apparent that the rule-of-thumb methods were not adequate, and consequently in 1905, Fuller and Thompson made some investigations of the effect of gradation of the aggregate upon the strength of concrete. Their work indicated to them that the densest concrete was the strongest, and accordingly they set about finding the ideal gradation of material, sand, and stone which would give the desired result. By means of mechanical or sieve analyses of many samples they finally obtained results which enabled them to plot a curve, since known as Fuller's Ideal Curve, representing the gradation of an aggregate which seemed to produce the strongest possible concrete with any given amount of cement.[1] This method was a distinct advance over the old rule-of-thumb methods, and by artificial grading very good results were obtained, especially with the lean mixes prevalent at that time.

But Fuller and Thompson's curve does not give workable material with the richer mixes in use today; it requires considerable computation and considerable mechanical labor in regrading sands, and as we shall see, there are other things which make this method impractical for present use.

Abrams' Studies.—About 1915, Duff A. Abrams, in charge of a laboratory supported by the Portland Cement Association, started an investigation to settle disputes which had been in progress for some time. His work involved the relationship between richness of mix, gradation of the aggregate, and amount of mixing water.

Bauer says, "The most important result of these investigations was the principle that with given concrete materials and conditions of test, the quantity of mixing water used determines the strength of the concrete, *so long as the mix is of a workable plasticity.*" The quantity of mixing water is expressed by a new term, the *water-cement* ratio which is the ratio of the volume of the mixing water to the loose volume of the cement. For a water-cement ratio of 1, 7½ gallons of water per sack of cement are used.

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[1] See Baker's "Masonry" or Bauer's "Plain Concrete."

So long as the material remains plastic, the lower the water-cement ratio, the higher the strength. Where the mix is so dry that plasticity is lost there is a decrease in strength. The accompanying curve (Figure 35) shows these relations very well. The hooked part of the curve at the left shows what the effect of dryness would be upon mixes of various richness. The figure shows how lean mixes become dry or harsh at a higher w/c ratio and therefore fall off in strength.

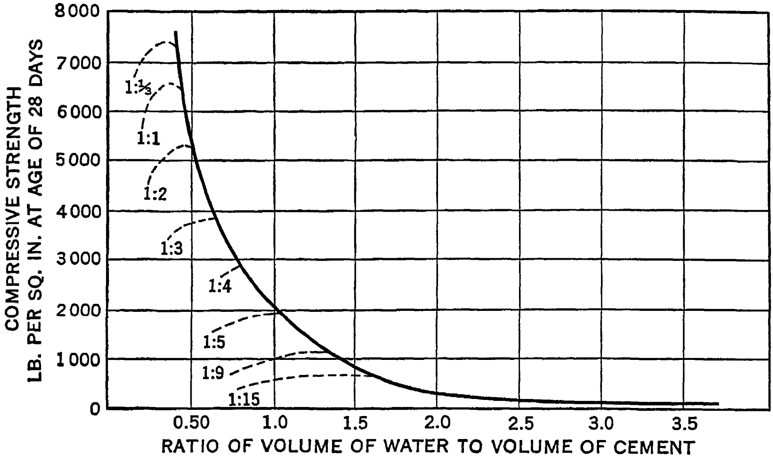


Figure 35. Effect of Ratio $\frac{\text{Volume of Water}}{\text{Volume of Cement}}$ on the Strength of Concrete. This curve is spoken of as Abrams' curve

The importance of this principle is at once apparent when we realize that specifications for modern concrete structures specify either the water-cement ratio to be used, or the required compressive strength at 28 days.

Fineness Modulus.—In his study of gradation of size of particles of the aggregate, Abrams used the sieve analysis as did Taylor and Thompson. He used a set of sieves made up as follows: Nos. 100, 48, 28, 14, 8, 4, ⅜ in., ¾ in., 1½ in.; and he determined the amount of the aggregate *coarser* than each of these screens. He then added the percentages of the amounts coarser than each of these screens and divided the sum by 100, getting a result which he called the *Fineness Modulus.* It was found that for a given mix and maximum size of aggregate there is an increase of strength with increase of fineness modulus up to about 6 to 6.5, the certain limiting value depending upon the size and kind of the aggregate.

The scheme for proportioning by this method was about as follows: The fineness modulus of coarse and fine aggregate is determined separately and then the proportion of fine to total aggregate is computed by means of a formula, from the determined values, and from the established value for fineness modulus of the combined aggregate.

The desired consistency is estimated and checked against the desired strength on a chart. This strength value is checked against the corresponding strength for a concrete of standard consistency. Then by use of the same chart the proper ratio of mixed aggregate to volume of cement is determined.

The amount of water for the desired strength or rather the water-cement ratio for the desired strength is determined from the strength, water-cement ratio curve, modified by the moisture in the aggregate.

Thus we learn that the strength of concrete at any age, determined by the selected water-cement ratio, is practically independent of the amount of aggregate, so long as the fresh mix is plastic and workable.

The plasticity and workability are controlled by the ratio of coarse aggregate to fine aggregate; by the ratio of total aggregate to cement paste, and also by the kind of aggregate.

The Fineness Modulus has never been accepted by engineers as the proper method for determining the proportions of the mix, for although it is partly satisfactory for well-graded aggregates, it sometimes produces harsh and unworkable concretes.

L. N. Edwards developed a method, as the results of some experiments which he made, based upon the conclusion that it was possible to proportion cement and aggregates on the basis of the surface area of the aggregate.

A combination of this method and that of Abrams was used by Young, who determined the strength by the water-cement ratio and the amount of aggregate by the surface area method. The difficulty with this method is that it gives no way of proportioning the coarse to the fine aggregate.

Talbot and Richard made some interesting studies at the University of Illinois. Their work seemed to show that the strength of the concrete depended upon the composition of the cement paste. The proportion of actual cement to the bulk of the cement paste was the basis of all of their discussion and they compared results by means of an index called the cement-space ratio. This method involves considerable experimental work as well as about a dozen computations, and has not been used to any extent in practical construction.

Trial Method.—Practice in the use of Abrams' computation method and consideration of results, and difficulties met in the field have led to the modification of the computation method for determining proportions, resulting in what is known as the *trial method.*

In the trial method the aggregate in a workable mix may be considered as suspended in a medium of cement paste. It is readily seen that there must be a sufficient amount of cement paste, thick enough to suspend the aggregate particles, and at the same time thin enough to make the mass sufficiently mobile. The most economical combination of materials will be the one in which a given amount of cement paste is made to carry the largest amount of coarse aggregate, with sufficient plasticity to meet the placing requirements.

Having decided upon the strength desired, refer to the curve of strength versus water-cement ratio (Figure 35), and select the proper ratio from the desired strength. Assuming the use of room dry aggregates, so that no free moisture is present therein, and using the above ratio, mix up a paste with a weighed amount of cement. This cement paste will be very wet, but as aggregate is added it approaches the desired consistency. After an insufficient amount of mixed aggregate in assumed trial proportions has been added, further additions may be made until the desired consistency is reached. The desired consistency is determined by means of the "slump" test, in which a hollow frustum of a cone 12 in. high and 6 in. in diameter at the bottom, and 4 in. in diameter at the top is used. The receptacle is placed on a flat surface and filled with concrete, carefully rodded and the cone is removed, allowing the material to "slump." The amount of the slump is measured, as shown in Figure 36.

(Courtesy of Portland Cement Association)

Figure 36. Measuring Slump to Determine Consistency of Concrete

From the known weights of the materials used and the unit weights of each, the actual volume of each constituent used in the mix may be determined.

As stated above, dry materials should be used throughout these determinations and subsequent corrections made for field operations.

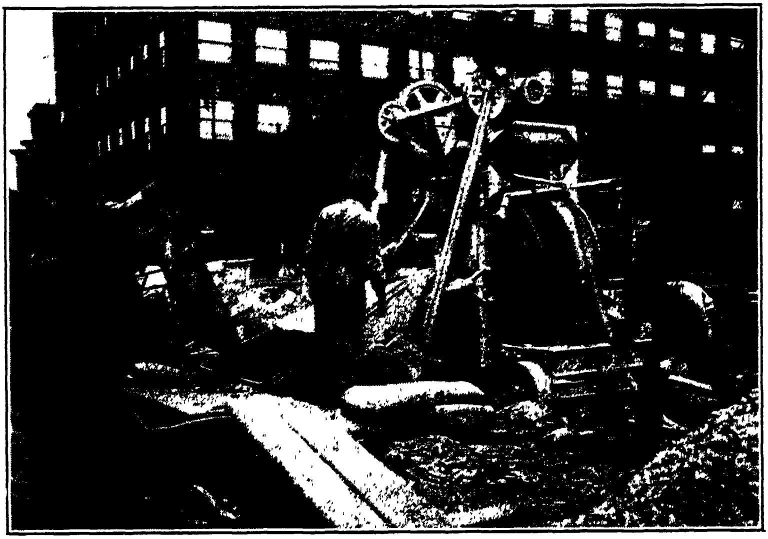
One of these necessary corrections is that for free water carried by the aggregates, which amount must be deducted from that calculated above by use of the water-cement ratio. To determine this free water, samples of the field aggregates should be thoroughly dried at 212° F. and the percentage of moisture driven off ascertained. Since the pores of the sand and gravel will reabsorb about 1% of water by weight (which will not be free to enter the cement paste), the percentages of free water present are those found by drying, less about 1%.

To get the proportions of the field mix by volume, from the weights determined above, divide the weight of the cement by its density (94 lb. per cu. ft.), and the weights of the sand and coarse aggregate by the weight, after drying, of 1 cu. ft. of damp, loose aggregate. To change this proportion (A) by volumes, to that where there is one part of cement (such as. 1 to 2 to 3½), divide each term in A by the volume of cement.

Another correction for the "bulking" of the fine aggregate in the moist condition must be made. This correction involves the ratio between the volume of 1 cubic unit of the dry aggregate and the volume which the same material will occupy when in field condition.

The addition of coarse aggregate increases the yield of concrete per bag of cement, but results in a harsh and unworkable mix. The addition of sand reduces the yield of concrete per bag of cement but makes a more workable mix. To obtain the best and most economical results, as much coarse aggregate as possible should be introduced and just enough sand added to make a workable mix of the proper consistency. In general, the ratio of fine to coarse aggregate is about one to two, but this varies somewhat with the grading of the coarse aggregate and the quality of the fine aggregate. The better the grading of the coarse aggregate, the less fine aggregate is required and the better the yield of concrete per bag of cement. Gravel in general requires less fine aggregate than broken stone.

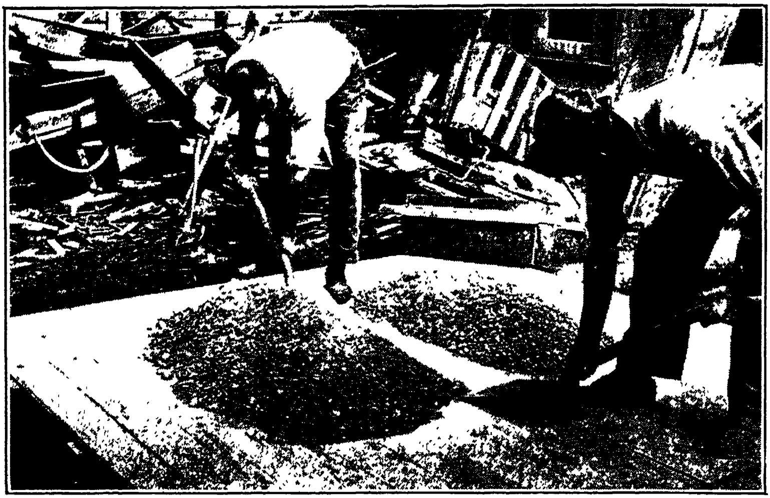
Mixing of Concrete.—Machine mixing is now universally carried out in batch mixers in which the proper proportions of material are charged together. These mixers consist of a chamber or drum which turns or rolls, causing the materials inside to roll over as gravity comes into action. Paddles fastened to the inside of the drum serve to work and mix the charge as it rolls, and in a short time such treatment produces a perfectly mixed material which is discharged and ready for placing. (See Figure 37.)



(Courtesy of Portland Cement Association)

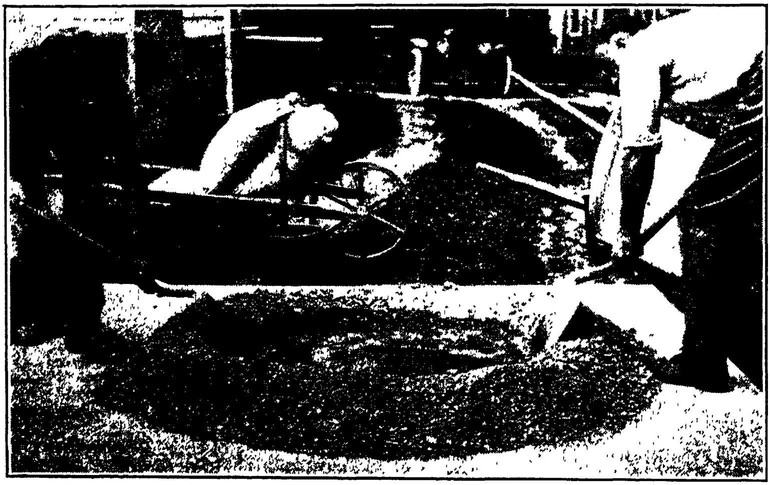
Figure 37. Batch Concrete Mixer at Work on Construction Job

Hand mixing is sometimes necessary and is satisfactory if



(Courtesy of Portland Cement Association)

Figure 38. Hand Mixing of Concrete—Mixing Materials Dry by Turning from One Pile to Another Three Times



(Courtesy of Portland Cement Association)

Figure 39. Hand Mixing of Concrete—Forming a Crater and Adding Correct Amount of Water, Turning Dry Material into the Center and Mixing Again

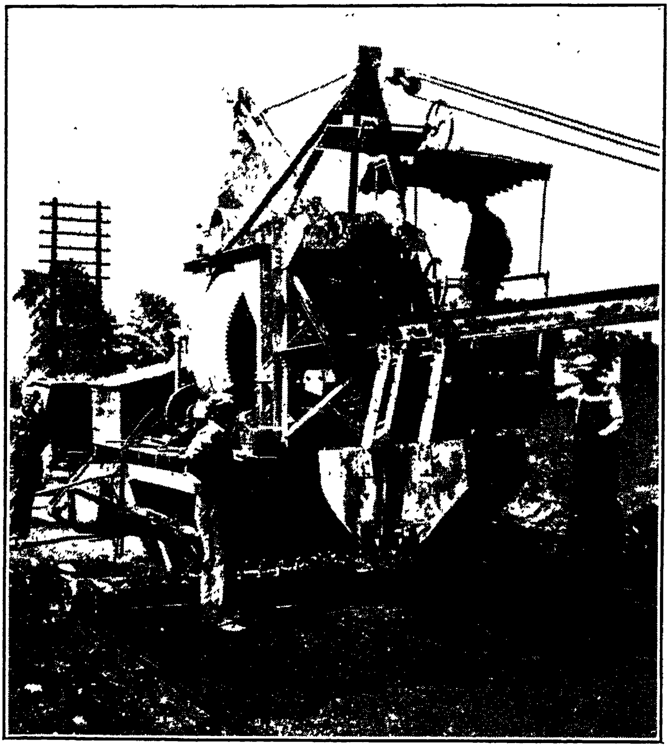
properly carried out. In this method the proper amounts of sand and cement should be mixed dry until the surface left by drawing the back of the shovel across the pile shows no streaks of unmixed sand and cement. Then the coarse aggregate should be added and the whole mixed again, dry. Finally the whole dry mass should be formed into a crater and the proper amount of water added. The dry material is then carefully turned into the water until the water is all absorbed, after which the wet mass is mixed until uniform, and of the proper consistency. (See Figures 38 and 39.)

Placing Concrete.—Plans for the placing of concrete must always take into account the time available. This is generally considered as determined by the time of set, as most engineers feel that any disturbance of the material after set has started is detrimental to the strength. The time of set is supposed to be determined at the standard temperature of 70° F. If the temperature of the mix is above this, the time of set is reduced somewhat and if below, the time is increased. Freezing temperatures stop the set entirely. It is quite apparent that these elements of time and temperature are very important in any building construction.

Movable Mixers.—One of the methods of placing concrete which is especially applicable in road building is that of following the work with a movable mixer, so that the batches are discharged directly at the place where they are to be used. The disadvantage of this method is the difficulty of bringing the raw material to the mixer as it moves along. (See Figure 40.)

Central Mixing Plants.—In most building construction, concrete is mixed in a central plant and distributed to different points by barrows or trucks; by hoists with buckets; cableways and buckets; or by chutes. Sometimes even belt conveyors are used for at least part of the distribution.

For economy of material, rather dry mixes are necessary; but for ease of handling, the wetter mixes are preferable. Old methods often secured this consistency by adding extra water, which resulted in reduced strength and sometimes caused separation of the aggregate, especially in the chute method of placing.



(Courtesy of Portland Cement Association)

Figure 40. Movable Mixer on Road Building Job

However, free flowing consistencies may be secured and strength maintained by proper gradation of the aggregate and by variation of the proportion of cement paste to total aggregate. For a given strength, wet mixes are not as economical a material as the dryer mixes, but this extra cost of material is often more than made up by the extra ease of placement.

Concrete once in the forms should be carefully tamped or rodded to allow air to escape and insure the perfect filling of the forms.

Placing Concrete Under Water.—One of the advantages of Portland cement is its ability to set and harden under water, and yet under many circumstances the cement may be washed away before it has a chance to set.

Sometimes the cement and aggregate are mixed dry and put in cloth sacks and the sacks then placed in the desired position. Water finally penetrates the mass and little material is lost by wash. There is no wet mixing and an inferior grade of concrete is, of course, the result, but as a practical method for difficult places it has proved effective.

The best method for depositing concrete under water where there is not much wash, is by means of the tremie pipe. This pipe must be long enough to reach from above the surface to the place where the concrete is to be deposited. Concrete is poured in at the top and when the pipe is filled the pipe is slightly raised allowing the concrete to spread out at the bottom. As more concrete flows out the pipe is slowly raised. This method is used for large masses where there is not much motion of the water.

Gunite.—A special way of placing concrete, or rather mortar, is by means of the "cement gun" where the dry mix of sand and cement is shot by compressed air, with water, against the surface to be covered. By this means surfaces may be built up with a comparatively high strength mortar. Proportions vary from 1 : 2½ to 1 : 5. Most of the work is done with mixes of 1 : 3½ or 1 : 4. (See Figure 41.)

Finishing.—Finishing of the surface of concrete is usually accomplished by a wooden float, a canvas belt, or a steel trowel.

The wooden hand float produces a plane, but rough, sandy surface. The long-handled wooden float produces the same kind of surface as the hand float but the surface is much more uneven. (See Figures 42 and 43.)

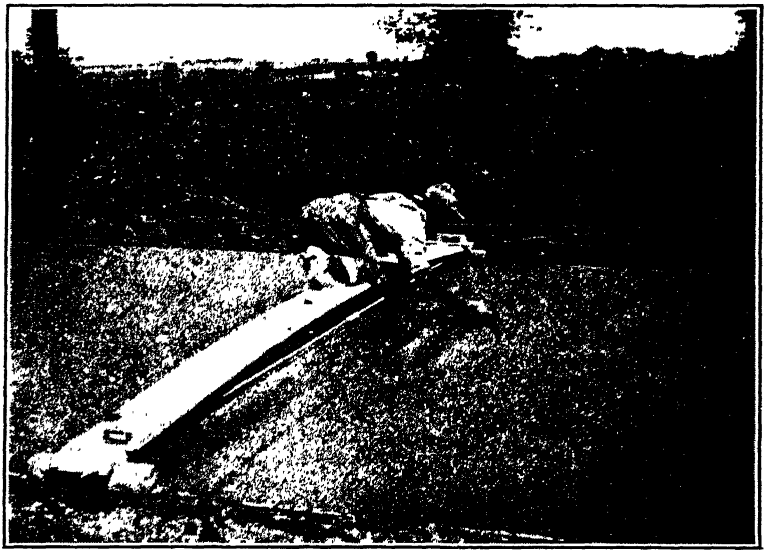
Canvas belts are used to produce a surface much the same as the wood float. They are used in road work and sidewalk surfacing. The surface is not generally quite as good, but the unit cost is much less.

(Courtesy of Portland Cement Association)

Figure 41. "Guniting" Piles

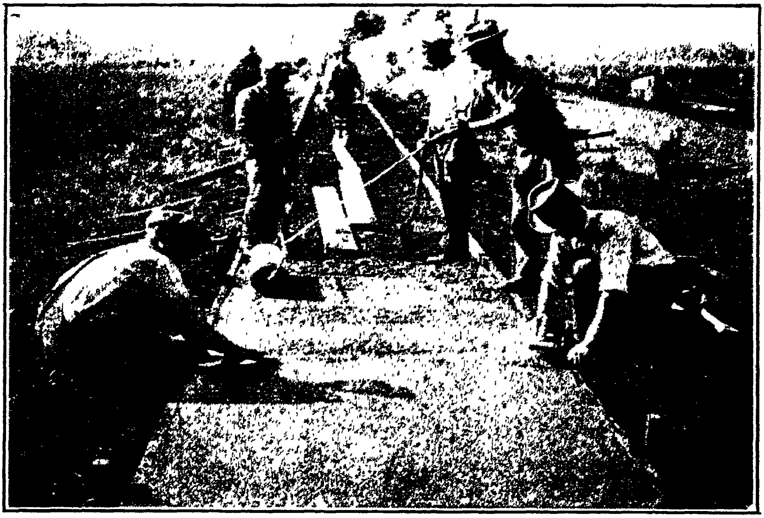
The steel trowel produces a very smooth surface. It draws the water and fine particles of cement to the surface and if care is not taken in removing the excess surface water and fine floating cement, flaking and dusting are apt to occur.

Bonding New Work to Old.—When new concrete is to be bonded to old, to produce a tight joint that will not crack, great care is necessary. The old surface should be removed and



(Courtesy of Portland Cement Association)

Figure 42. Finishing with Hand Float Each Side of Joint



(Courtesy of Portland Cement Association)

Figure 43. Sidewalk Finishing

he exposed part left rough and carefully cleared of dirt and lust, washed, and left wet. It should then be scrubbed with bristle brush dipped in a neat cement paste of fairly thin onsistency. A rich mortar should then be prepared and applied y considerable impact to the surface as prepared, after which t is ready to receive the regular concrete mix as it is to be sed in the construction. Tension joints in reinforced concrete nade this way are known to be stronger than the ordinary mix. Material patched in this manner and subject to the action of vater and frost have remained perfectly sound after years f service.

Protection of Concrete.—After placing concrete it must e protected from the sun and wind. The chief purpose of uch protection is to prevent evaporation of the water. If the oncrete becomes too dry during the period of setting, it will ever develop its full strength.

One of the most important problems of concreting in cold veather is protection against low temperatures and freezing. Concrete which freezes before the final set is permanently lamaged and may be completely ruined; and concrete cured at emperatures below 50° F. never attains its full strength. In old weather all the materials for the concrete should be heated up to as high as 125° to 150° F. and after the material is placed it should be protected by means of canvas as quickly nd effectively as possible. Where possible, stoves should be erected and fires maintained, for the higher the temperature, within reasonable limits of course, the quicker the concrete will set and harden and the higher the strength.

Curing.—One of the most important features of proper concreting is the curing of the material after it is placed. If concrete is to gain its greatest strength it must have plenty of moisture and moderate heat. Although the amount of water for actual hydration of the cement is not over 10% of the weight of the cement, the actual mixing water is very much more, often more than 50%. If this mixing water is retained in the concrete there is sufficient water to secure the proper development of strength. On the other hand, if the concrete is allowed to dry out too soon the strength will not be developed and the surfaces will chip and flake and dust, and have poor wearing qualities in general. Curing is simply the prevention of the evaporation of the mixing water. Temperature should, of course, be maintained as high as practicable.

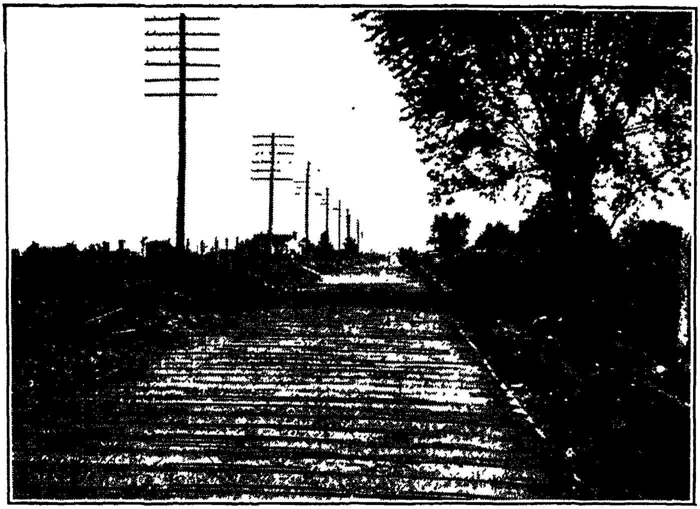
The greatest benefit from curing is secured during the first 3 days. After that there is some additional benefit up to 10 days or 2 weeks, but engineers do not generally consider it worth while to keep the concrete wet longer than a fortnight.

Where forms are used they should be kept in place as long as possible. If it is necessary to remove them before proper curing is secured, the exposed surfaces of the concrete should be sprayed as often as is necessary. Curing is often omitted in building construction, but many difficulties would be avoided if more attention were given to this practice. However, in road building, curing is an important part of successful practice. Pavement surfaces must be strong to bear the wheel loads and they must be hard and firm to withstand the abrasion. Poorly cured road surfaces are not at all satisfactory.

Covering with damp earth or straw as soon as the concrete is set is one method often used. A layer of about 2 in. of earth or about 6 in. of straw is often used, and this is kept wet for the requisite time. (See Figure 44.)

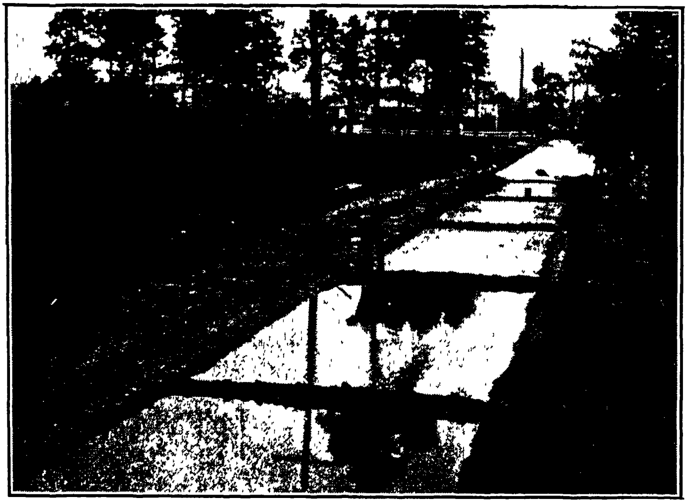
Ponding is a method of curing often used in road building. After the concrete has become hard earth dikes are built along the edges of the pavement and transverse dams built often enough to make a series of enclosed areas approximately square. The areas are flooded for the requisite time and effective curing is secured. This method uses considerable water, and trouble is sometimes experienced when the dikes break, but it has found considerable favor with contractors. (See Figure 45.)

Flake calcium chloride is sometimes sprinkled on to the



(Courtesy of Portland Cement Association)

Figure 44. Curing Concrete Roadway Using Wet Burlap for 72 Hours



(Courtesy of Portland Cement Association)

Figure 45. Curing Concrete Roadway by Ponding

pavement at a rate of about 2 to 2½ lb. per sq. yd. This salt is deliquescent, and after a short time will absorb enough water from the atmosphere to dissolve itself. The solution diffuses into the surface of the concrete and maintains a damp surface for a long time. There is a danger that too much of this material may be used and the effect may be more harmful than beneficial.

Calcium chloride curing is clean and comparatively inexpensive and once applied needs no further attention. There is nothing to clean off and when sufficient strength is attained the road may be opened to traffic at once.

Water glass is sometimes used to seal up the surface of the concrete, to prevent evaporation. Although the action is entirely different, the method has the same advantages as the calcium chloride method.

Gain of Strength of Concrete with Age.—All the discussion on the previous pages has been based on the strength at definite age periods, but consideration of the rate of gain of strength is important. The criterion for Abrams' tests and for most others up to the present day has been the 28-day test. Specifications generally are based on the results of the 28-day test. However, the progress of the setting and hardening and gain of strength is not uniform for all kinds of cement and not uniform for all mixes.

Rich mixes with low water-cement ratios develop strength much more rapidly than lean mixes, with high water-cement ratios of the same consistency.

To be specific, a concrete of a certain consistency which had a water-cement ratio of 1.2 had a 28-day strength of 2,700 lb. per sq. in. Another concrete of the same cement, and same consistency with a water-cement ratio of 0.6 had a strength of 2,700 lb. per sq. in. at 3 days. The 28-day strength of this latter mix was 6,100 lb. per sq. in. Some of the special cements are much more rapid in their strength gaining capacity than that, and some of the high aluminate cements will give concretes as strong in half a day as ordinary cement concretes will be in 4 or 5 days. For certain types of work this high early strength is valuable, but for given mixes and water-cement ratios they all arrive at about the same strength at the 28-day period, so that for a reliable criterion the 28-day strength will doubtless stand unmodified for general commercial use.

Waterproofing of Concrete.—A considerable amount of research has been done on the problem of waterproofing of concrete. Some patent waterproof cements have been put on the market. They are nearly twice as expensive as the regular brands and there is not entire agreement as to their efficacy. Very much can be done in the way of waterproofing with the regular brands of cement if proper care is taken. Proper mixing of mortars fairly rich in cement insures a homogeneous, dense mass, and if curing is properly done such concretes will be quite waterproof. Waterproof cement alone does not insure waterproof concrete.

Hydrated lime is sometimes added at the rate of 3 to 5 lb. to the sack of cement, with fairly good results.

Mixtures of soap and alum have also been used, but the lasting qualities of concrete treated in this way have been questioned. This soap and alum method has been used as a surface wash. The soap is first applied as a hot, aqueous solution and the alum applied after about 24 hours, also as a weak aqueous solution.

Bituminous Coating and Waterproof Membranes.—When the side of the concrete from which the water will be liable to enter is accessible, hot tar or asphalt may be used as a wash or coating. The lighter materials like water-gas tars will penetrate considerably and the heavier ones will form a thick coating perfectly impervious to water. A still more effective waterproof barrier may be secured by use of layers of fabric like roofing felt cemented to the work by hot asphalt or coal tar washes.

Durability of Concrete.—The durability of concrete depends upon the materials from which it is made, the richness of the mix, and the curing. Otherwise, it is much like any other stone and subject to the same kind of weathering action.

Reinforced concrete which contains embedded steel may be subject to disintegration from electrolysis, so that conditions which would be liable to lead to danger from that source should be avoided.

Concrete Building Blocks, Brick, Pipe, etc.—Concrete building blocks are generally made of relatively fine aggregate. If coarse aggregate is used at all it should not be over ¾ in. Gravel is generally considered as preferable to broken stone. The proportions vary from 1:2:3 to 1:3:5 where coarse aggregate is used. If mortar alone is used, the mixture may vary from 1:3 for medium sands to 1:4 for coarse, well-graded sands.

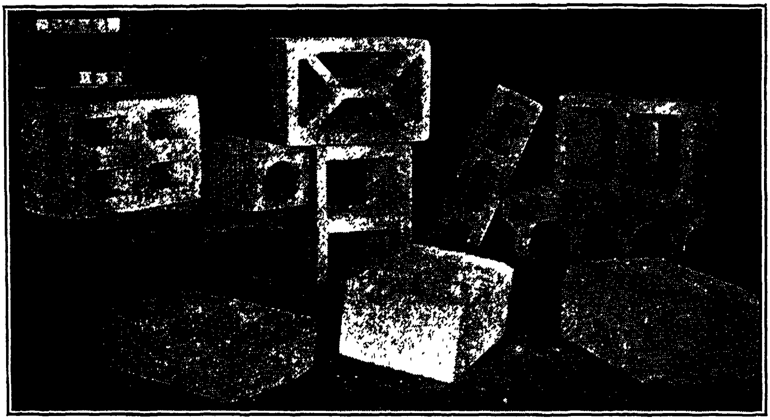
Concrete blocks may be made of either dry or slush consistency, but the dry consistency is much more universal. (See Figure 46.) The main advantage of the dry consistency method is that the mold may be removed as soon as the block is formed and it will retain its shape from the beginning. Blocks made of slush consistency must remain in the mold until after they have hardened, so that this process requires a great many molds for any considerable production.

Blocks made by the dry process have a deficiency of water from the beginning and cannot be expected to reach the strength attainable with wetter mixes; very inferior blocks often result where blocks are allowed to dry before they set. It is important that blocks made by this process be kept moist during the first few days of the hardening process.

Concrete blocks should show a strength of 600 to 800 lb. per sq. in. of gross area in 28 days to be considered satisfactory.

The extreme variability of strength of blocks from different manufacturers, as well as the variability in strength of blocks made by the same manufacturer, have led to a considerable distrust of concrete blocks as a building material. Most city ordinances require rigid inspection and testing of any blocks which are to be used for construction of bearing walls.

Concrete is extensively used for sewer pipe and to some extent also for brick. The methods of manufacture of these materials vary with the specifications which they have to meet. Some are made by the dry process but the stronger, more impervious, higher grade materials must be of slush consistency to meet the specifications.



(Courtesy of Portland Cement Association)

Figure 46. Various Types of Concrete Blocks

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CHAPTER 5

STRUCTURAL CLAY PRODUCTS

Common Brick.—Common brick are made from ordinary clays or shales. Although there may be considerable variation in the color of the raw material, most of the brick burn to a red. Some clays, especially those rich in lime, may burn to a creamy white.

In the manufacture of brick the clay or shale is reduced by grinding, and addition of the proper amount of water, to a mud. This mud may be either soft or stiff, according to the type of brick to be made.

Soft mud brick are made in machines which press the mud into molds which are later removed, leaving the formed brick on a bottom board. *"Sanded"* or *"sand-struck"* brick are made in a mold which has been dusted with dry sand so that the mold may be easily withdrawn. Much of the sand remains on the surface of the brick and gives it a sanded-surface appearance.

"Slop brick or water-struck" brick are made in the same way as the sanded brick, except that the mold is dipped in water in order to make the brick slippery so that the mold may be withdrawn. These brick are easily distinguished from the sanded brick. Comparatively few water-struck brick are seen in ordinary building construction.

Stiff mud brick are made from a mud of a much stiffer consistency, which is forced through a die in the form of a prism and afterward cut by wires into the proper size for brick. These *wire-cut brick* are easily distinguished by the marks from the cutting wires, as well as by the scoring from the die through which they were pressed.

Drying of the Brick.—After the brick has been formed, it is necessary to remove the excess water slowly, by evaporation, before the burning process. Drying racks are situated so as to permit easy access of drying breezes, but they are protected to shield from the extreme heat of the high sun.

Burning.—When the brick are sufficiently dried they are piled in a kiln for burning. There are various types of kilns, but all are made for the same purpose, i.e., to burn the brick at a temperature nearly sufficient to vitrify them. Modern kilns and improved methods of burning produce a very uniform product, but the older updraught scove kilns did not produce uniform results, and as a great deal of brick is still burned in such kilns the *classification according to position in the kiln* is important.

Arch or clinker brick are those directly over the fires in the furnace arches. They are apt to be shrunken, warped, dark-colored, hard and glassy, but very strong. They have a poor appearance but are sometimes used for piers or places where high strength is required.

Body, cherry, red, or hard brick come from the body of the kiln and are the best bricks for building purposes. They are true in shape and when struck together give a good ring; they have been burned to just below the heat where vitrification begins.

Salmon or pale bricks are those which have not received heat enough to burn them properly. They are soft and weak and sound dead when struck together. They weather easily and cannot be used where much strength is required.

Good building brick should have a fine and uniform texture; should contain no fissures, sand seams, lumps of lime, bubbles of air, or pebbles. Richardson says of building brick, "In compactness and uniformity of texture, hand-molded brick stands first; machine-molded, soft-mud brick second; machine-molded, stiff-mud brick third; and dry clay brick fourth."

TABLE 2. CRUSHING STRENGTH OF BRICK PIERS

(Watertown Arsenal Tests, 1904)

Age 6 months

Description of Brick	Compressive Strength lb. per sq. in.			Per Cent of the Average Crushing Strength of Brick		
	Neat Portland	1 Portland 3 Sand	1 Lime 3 Sand	Neat Portland	1 Portland 3 Sand	1 Lime 3 Sand
FACE BRICK						
Dry-pressed face brick.	2,880*	2,400	1,517	26	21	13
Re-pressed mud brick. .	1,925	1,670	1,260	28	25	19
COMMON BRICK						
Wire-cut stiff-mud brick	4,021	2,410*	1,420	31	19	11
Hard sand-struck brick.	4,700*	1,800*	994	42	16	9
Hard sand-struck brick.	1,969	1,800	733	44	40	16
Hard sand-struck brick.	1,400	1,411	718	24	24	12
Light-hard sand-struck brick...............	1,510*	1,519	732	23	23	11
Light-hard sand-struck brick..............	1,061	1,224	465*	20	23	9

* Tested at the age of 1 month.

TABLE 3. SAFE WORKING STRESSES FOR BRICK MASONRY

(Recommended by a Committee of Chicago Engineers and Architects as Reported by Mills)

Description of Brick	Kind of Mortar	Safe Load lb. per sq. in.
Paving brick..........................	1 : 3 Portland	350
Pressed and sewer brick (strength 5,000 lb.)...........................	1 : 3 Portland	250
Select hard common brick (strength 2,500 lb.)...........................	1 : 3 Portland	200
Select hard common brick (strength 2,500 lb.)...........................	1 Portland, 1 lime, 3 sand	175
Common brick (strength 1,800 lb.).....	1 : 3 Portland	175
Common brick (strength 1,800 lb.).....	1 : 3 Natural	150
Common brick (strength 1,800 lb.).....	1 Portland, 1 lime, 3 sand	125
Common brick (strength 1,800 lb.).....	1 : 3 lime	100

Compressive Strength.—The compressive strength of building brick from various localities is quite variable, ranging from 3,000 or less to over 20,000 lb. per sq. in. Compressive strength of brick is ordinarily of little importance since the proportion of mortar is so high and thus the mortar strength is ordinarily the determining factor. The strength of brick piers and masonry is indicated by Tables 2 and 3, as reported by Mills.

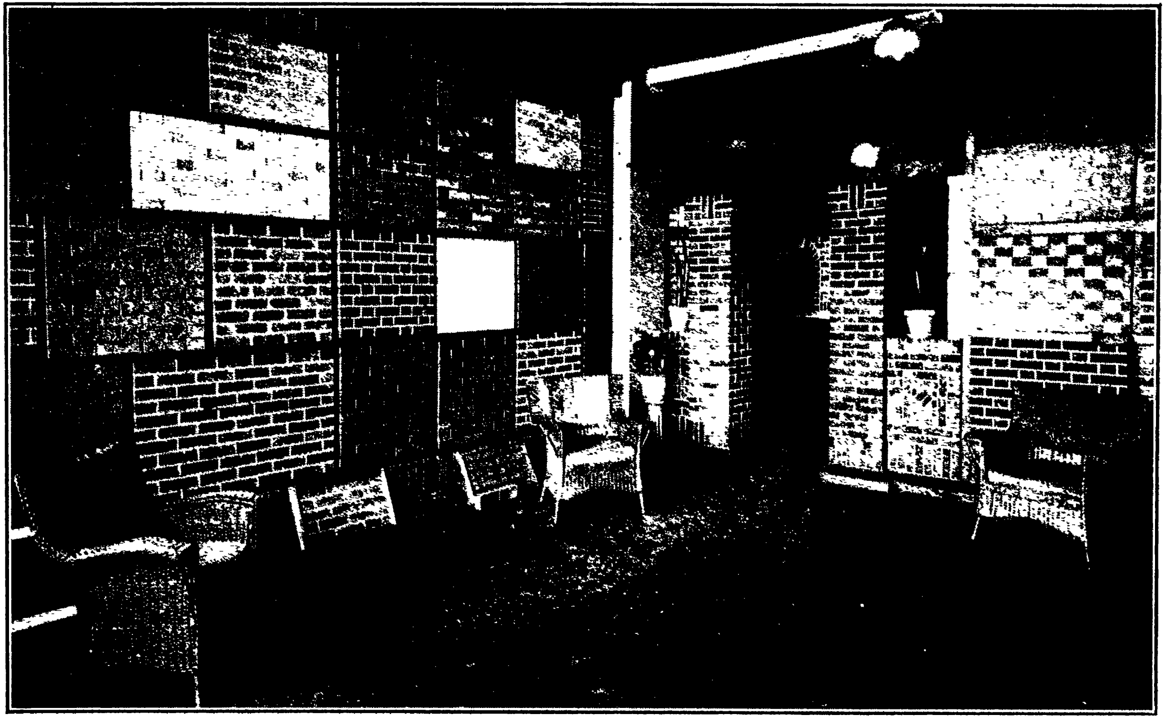
Pressed brick is usually a stiff-mud brick which has been subjected to a high pressure to make it more regular in form and increase its strength and density. A soft-mud brick may be re-pressed after being partially dried to make it more even in form and improve its strength. Pressed or re-pressed brick are used for face brick where a smoother, more regular appearance is desired.

Paving brick is a special block of hard-burned clay made especially for paving purposes. These blocks are generally made from special shale and are burned so that they are very hard, strong, and tough to stand the abuse to which a pavement is subjected.

Architectural Face Brick.—There are many special types of brick made with special face surfaces for special architectural effect in building construction, but it is beyond the scope of this book to go into detail regarding them. Figure 47 shows some of the effects which may be produced by proper selection and design.

Sand-Lime Brick.—Although there have been several classes of brick made by combining sand and lime together, there is only one kind of any commercial importance which is really entitled to the name of "sand-lime brick."

Sand-lime bricks are made by properly combining a comparatively pure, well-graded, not too coarse sand with granulated or pulverized lime, after which water is added and the whole thoroughly mixed in a pug mill. The bricks are then



(Courtesy of Common Brick Manufacturers Assn.)

Figure 47. Effects Secured by Proper Selection and Arrangement of Various Types of Brick

formed by pressing into molds and are hardened in closed chambers where they are exposed to an atmosphere of steam under a pressure of 100 to 150 lb. per sq. in.

Although it has never been theoretically accepted that a very different chemical reaction to produce hardening takes place in the steam cylinders than would take place in the air, it is certain that a brick of much higher strength is formed than can be accounted for by the production of a simple calcium carbonate binder.

Sand-lime bricks are used for general construction purposes where pressed brick would be used. They are often used for basement walls where a pleasing, light-colored, brick-faced surface is desired.

Fire Brick.—Fire brick which is able to withstand moderate heat has been manufactured for many years, but recently industrial requirements have made it necessary to produce brick which will not only stand more elevated temperatures but which will also stand the scouring action of slags and atmospheres encountered in metallurgical furnaces.

These brick may be classified according to the chemical reaction which they resist; that is to say, acid, basic, and neutral.

Acid Brick.—There are three kinds of acid brick: fire clay brick; silica brick; ganister brick.

Fire clay brick differ from ordinary brick clays in that fluxing impurities such as iron, lime, magnesia, and the alkalis are practically absent.

Fire clay is generally mixed with flint clay, burnt fire clay, or sand, or some other refractory material to prevent shrinkage during burning and drying. It is one of the most refractory of furnace linings. Low-grade fire clay brick will not stand a temperature over 2,500° F., but high-grade material should stand as high as 3,500° F. to 4,000° F.

Silica brick is made from very pure silica sand, or ground silica sandstone mixed with a small percentage of lime or sometimes fire clay for binder.

These bricks expand on heating to high temperatures in the furnaces instead of shrinking as fire clay brick do, and this must be allowed for when they are set.

Silica brick is somewhat more refractory than the ordinary run of fire clay brick, but is stated to be slightly less refractory than the highest grade. Silica brick is brittle and must be handled carefully.

Ganister brick is made from ganister rock which is a sandstone containing about 10% clay. It is therefore a material intermediate between fire clay brick and silica brick.

Basic Brick.—There are two kinds of basic brick: magnesia brick and bauxite brick.

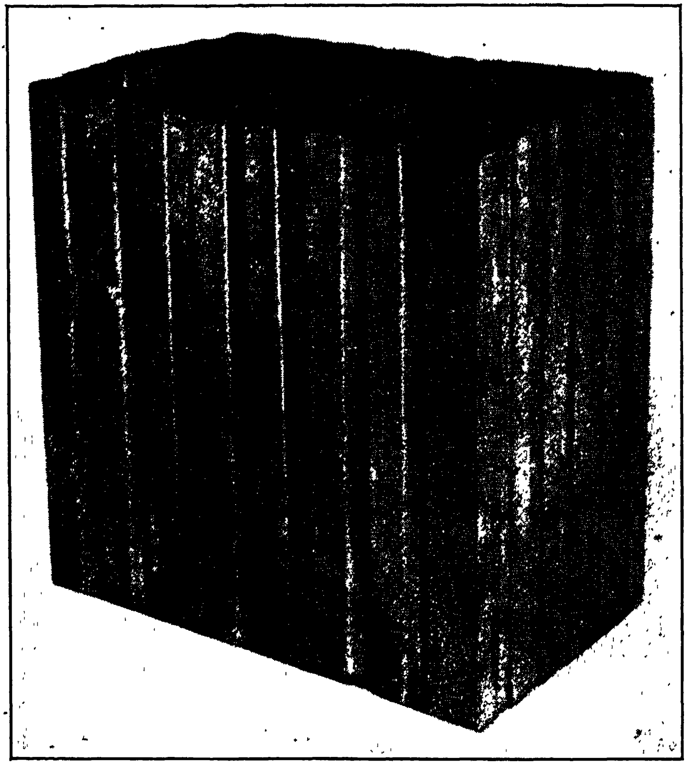
Magnesia brick is made from magnesia which has been properly calcined, tempered, pressed, and burned. Styrian magnesia from Austria is considered to produce brick somewhat more refractory than that made from the ordinary material. Dolomite (a double carbonate of lime and magnesia) is sometimes used to make magnesia brick, but it produces an inferior material and can only be used for lower temperatures.

Bauxite brick. Bauxite is a mineral consisting largely of alumina with some silica, a little iron oxide, and some slight other impurities. Bauxite brick is made by grinding this mineral with about 15% to 30% of fire clay, tempered with water, and then molded into bricks and burned. When properly burned they are highly refractory but they shrink so much when heated to high temperatures that they have not come into very extensive use.

Both magnesia and bauxite brick are weak structurally.

Neutral Brick.—For certain purposes a brick which is neither acid nor basic in reaction is desired, and for this purpose chromite (a chrome iron ore) is principally used. Chromite used alone is practically without binding power, and fire clay or bauxite is usually mixed with it to act as a binder when the brick is burned. At best, chrome brick is low in mechanical strength and is somewhat less refractory than magnesia brick.

Building Tile.—Building tile are made of plastic clays, or shales mixed with clay, which will burn to a hard, dense structure at a fairly low temperature. They may be classified according to the service which they are to perform.



(Courtesy of Structural Clay Tile Association)

Figure 48. Structural Clay Building Tile 8 in. by 12 in. by 12 in.

Load-bearing tile are hard-burned, strong tile of such section and design that they will satisfy the building ordinances for bearing walls. A great many styles and shapes are made to suit special types of construction.

Load-bearing tile are required according to specification to bear the word "load-bearing" as well as the initials of the manufacturer.

An ordinary 8 in. by 12 in. by 12 in. block of building tile is shown in Figure 48. Various styles and shapes are used and may be designed for either *end* or *side construction*, that is to say, in some tile construction the air spaces run vertically while in others they run horizontally.

Tile are classified as hard, medium, or soft.

TABLE 4. STRENGTH OF STRUCTURAL TILE

Class	Absorption, Per Cent		Compressive Strength Based on Net Area lb. per sq. in.			
			End Construction		Side Construction	
	Mean of 5 Tests	Individual Maximum	Mean of 5 Tests	Individual Minimum	Mean of 5 Tests	Individual Minimum
Hard..........	12 or less	15	4,600 or more	3,000	2,400 or more	1,700
Medium........	16 or less	19	3,200 or more	2,250	1,600 or more	1,100
Soft...........	25 or less	28	2,000 or more	1,400	1,200 or more	850

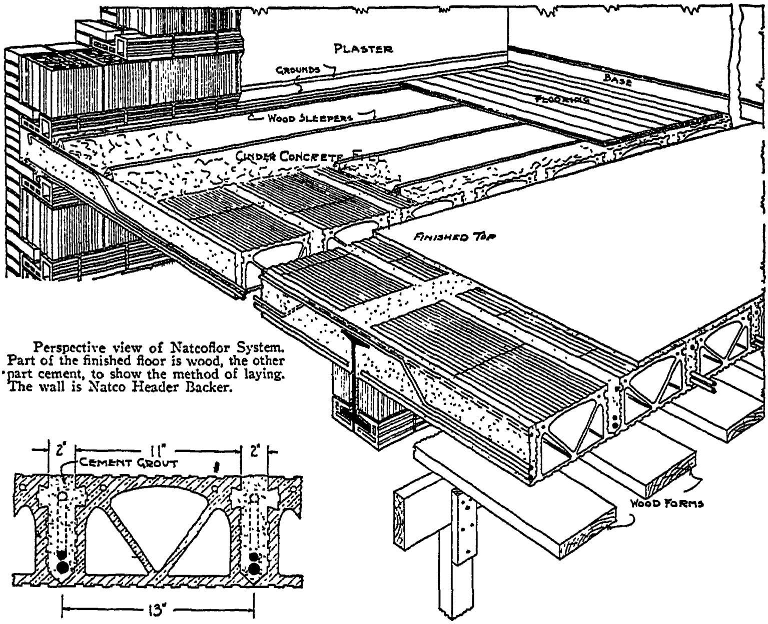
As different types of clay are used in the manufacture of tile, color cannot be taken as indicative of classification.

Where end-construction tile are used on the side they shall meet the requirements of that construction, and vice versa.

All tile shall be so designed that substantially the same masonry strength will be developed in all wall thicknesses for which they are to be used.

Structural tile for plastered wall has a surface which is either scored or combed to afford better adhesion for the mortar, but for unplastered walls it is often made with a glazed surface (see Figure 48).

Partition tile may be soft, or *non-load-bearing tile,* as it is not expected to carry more than the weight of the partition itself.


Plaster
Grounds
Base
Flooring
Wood Sleepers
Cinder Concrete Fill
Finished Top
Wood Forms
2"
11"
2"
Cement Grout
13"

Perspective view of Natcoflor System. Part of the finished floor is wood, the other part cement, to show the method of laying. The wall is Natco Header Backer.

Notice in the detail view, how the tile meet at the bottom, to form an all-tile ceiling.

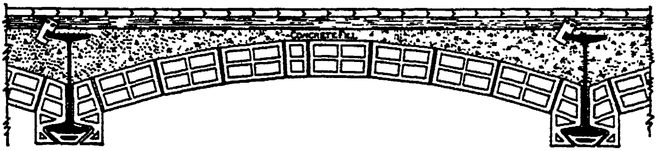
(Courtesy of National Fireproofing Co.)

Figure 49. System of Fireproof Floors

Fireproofing tile may be either load-bearing or non-load-bearing tile so long as it fulfils the other specifications for the fireproof covering.

Figure 49 shows a typical floor and wall construction illustrating exceedingly well the adaptability of building tile to modern construction. Figure 50 shows arch floor construction using so-called "side construction."

Roofing tile must be hard-burned, strong, and non-porous. It is made by a stiff-mud process similar to that employed for the manufacture of stiff-mud, re-pressed brick. It is made in several colors to suit the trade.



(Courtesy of National Fireproofing Co.)
Figure 50. Segmental Arch Floor

Sewer Pipe, Drain Tile, and Conduit.—*Sewer pipe* is intended for use in carrying more or less objectionable waste waters; it is generally buried deeply in trenches and covered. Accordingly, it is made of hard-burning clays molded to form and burned to incipient vitrification. It is generally salt-glazed to insure a smooth and impervious surface. Sewer pipe must possess high strength to stand the earth pressure about; it must be non-porous and non-absorptive to prevent seepage into the surrounding soil, and it must present a smooth surface so as to obstruct the flow of the fluid burden as little as possible. Such pipe is generally made in 3-ft. lengths and up to about 42 in. diameter. They are made bell-mouthed on one end so that they may be fitted together and the joint sealed with mortar. A 1 : 1 Portland cement mortar is generally used to fill the joint.

Drain tile are simple shapes designed to be laid end to end, that is, butted to allow water to enter at the junction. Some drain tile are extremely soft and porous to allow an inward seepage of the ground water, but other makes are very hard and sometimes even salt-glazed.

Conduit. Clay conduit, made of hard-burned, salt-glazed material, traversed by several longitudinal ducts, are often used for carrying underground cables and wires. These are often laid in trenches and surrounded by a concrete grout for permanence.

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Proceedings of the A. S. T. M.

CHAPTER 6

BUILDING STONE

Definitions.—The term "building stone" is ordinarily understood to include all forms of igneous, sedimentary, or metamorphic rocks that are used for structural or decorative purposes. In this text it is unnecessary to go into the geological and mineralogical aspects of the subject, and only a general survey is given.

The material of building stone is, in general, called rock. *Rock* is defined as a mineral aggregate.

A *mineral* is generally defined as a natural inorganic element, or compound, with a fairly definite chemical composition.

Igneous rocks are either "eruptive" or "irruptive," according as they have flowed out over the surface of older formations, or simply appear at the surface only after material which originally covered them has been carried away.

Sedimentary rocks occur in stratified beds where material has become consolidated from particles of decayed rocks which have been deposited from streams of water.

Metamorphic rocks are those which have been changed by either pressure or heat or both from rocks which were originally either igneous or sedimentary.

Mineral of Building Stone.—The number of minerals essential to any one kind of building stone is exceedingly small. A general description of the most important of the minerals will afford some knowledge of the constituents of rock.

Quartz.—Quartz is silicon dioxide. It is very insoluble and extremely hard, being 7 in Moh's scale of hardness. It is the chief constituent of most sea beach and river plain sands.

It is found in sandstones, mica schists, granites, gneisses, etc. It is extremely durable.

Feldspar.—The name feldspar applies to any one of a group of minerals which have many characteristics in common.

Orthoclase feldspar is potassium aluminum silicate. Its color varies from deep pink to whitish pink.

Plagioclase feldspar is either sodium or calcium aluminum silicate. Its color varies from gray to white. The hardness of feldspar is from 6 to 6.5. They are less durable than quartz.

Micas.—*Muscovite mica* or "white mica" is an orthosilicate of aluminum, potassium, and hydrogen. When free from iron it is quite durable. Its hardness is only 2.3.

Biotite mica is also an orthosilicate of aluminum, potassium, and hydrogen, but it also contains magnesium and iron. It is often called "black mica" or "iron mica." Its hardness is 2.8, but it disintegrates rather rapidly on exposure, and is an undesirable mineral in stone, especially in exposed places. Micas are easily split into thin, tough, elastic sheets.

Amphibole commonly occurs as *hornblende*, *tremolite*, or *actinolite.*

Hornblende is a complex silicate of iron, lime, magnesia, and alumina. Its color is dark green to black; its hardness is 5.5 to 6; it weathers fairly well. *Tremolite* is a silicate of calcium and magnesium; its color, white to gray; its hardness, 5.5; it weathers poorly. *Actinolite* is much like tremolite, but it has part of the magnesium replaced by iron. Its color is bright green or grayish; it is equally objectionable in building stone with tremolite.

Pyroxenes are metasilicates of calcium, magnesium, and iron, ranging in color from bronze through green to black. They occur as *augite, hypersthene,* or *enstatite.* The hardness is about 5.5. They somewhat resemble hornblende and weather fairly well.

Hydrous silicates. Three hydrous silicates of considerable importance deserve mention. They are, *chlorite, serpentine,* and *talc.*

Chlorites closely resemble mica in appearance, but they contain much more water and are inelastic and brittle.

Serpentine is a hydrous silicate of magnesium. It is green to greenish black and has a soapy "feel." It is much softer than marble is though it sometimes occurs in marbles in green patches.

Talc is another hydrous silicate of magnesium containing less water and more silicon dioxide than serpentine. The massive form known as steatite or soapstone has many common uses. It is very soft, hardness about 1.

The *carbonates* that occur as essential rock minerals are calcite, aragonite, and dolomite. *Calcite* and *aragonite* are both calcium carbonate, but they differ in their crystal formation.

Calcite is white when pure, but quite variable in color with slight impurities. Its hardness is 3; it effervesces in hydrochloric acid, and dissolves slowly in water containing traces of acid; it is not very durable.

Aragonite has a hardness of 3.7. It is otherwise similar to calcite.

Dolomite is a double carbonate of calcium and magnesium. Resembles calcite; hardness 3.5 to 4; less soluble than calcite but not very durable.

Gypsum is a hydrous calcium sulphate. It is the only sulphate that is an important mineral constituent of rock. It is white or nearly colorless. Alabaster is a fine translucent variety. If gypsum loses its water of crystallization it is called anhydrate, a substance which has been used as white marble. Such practice should be discouraged, however, for if it reabsorbs water it expands, producing disastrous results.

Oxides, carbonates, and sulphides of iron as mineral constituents of rock are often found and are practically always objectionable. Discoloration followed by weakening of the material occurs as disintegration progresses.

Physical Properties.—The most important physical properties of building stone are color, texture and state of aggregation, hardness, compressive strength, and transverse strength.

Color is an important factor in the selection of stones from an architectural standpoint. Color may be due to the natural color of the essential minerals; or to pigment included in the impure mineral. Variations in ability to reflect or absorb light affect the color to a large extent. Color is not always permanent, and changes often occur where the stone is exposed to the atmosphere.

Texture of building stone depends upon the size of the particles of the assemblage of minerals which constitute the rock. It ranges from very coarse-grained granite phase, known as "pegmatite," through the conglomerates or "pudding stone" and breccias to the fine texture of basalts and slates.

The *state of aggregation* refers to the relative strength of the bonding material or cement between the grains and the grains themselves.

Hardness of building stone is understood to mean its resistance to abrasion. It depends not only upon the hardness of the individual minerals but upon the texture and state of aggregation.

Density is the degree of compactness. The more dense a stone, the less water it will absorb, and therefore the less the danger from injury by freezing. Compressive and tensile strength is roughly proportioned to the density.

Compressive strength depends upon the mineral constituents, the texture, and the state of aggregation. It is a variable quantity for any class of rock.

Transverse strength refers to resistance to bending. Building stone is far more apt to break transversely than by crushing.

Such breaks are generally caused by poor bedding, or by unequal settlement.

Weathering of Building Stone.—The term weathering of stone includes chemical and mineralogical as well as mechanical changes which occur under the influence of atmospheric exposure.

Pure water has little, if any, solvent action on building stone, but water is seldom pure. It contains dissolved gases of various kinds, particularly oxygen and carbon dioxide. Nitric acid and ammonia are often observed in the atmosphere, and sulphur dioxide in the vicinity of places where large quantities of coal is burned, is very noticeable.

Atmosphere laden with such chemical agents as these, attacks and dissolves various rock minerals, favoring disintegration to a high degree.

Snow often carries a higher percentage of the deleterious agents than rain, and lodgment of snow in exposed places affords ideal conditions to promote weathering.

Vegetable Growth.—Vegetable growth on rock surfaces retains moisture and keeps the rock damp. Roots penetrate the crevices and expand, exerting great disruptive force, and after the organic acids formed in the roots have dissolved some of the mineral substance, the surface easily becomes gradually disintegrated.

Bacteria.—Where conditions favorable for the growth of bacteria occur on rock surfaces, ammonia and nitric acid are formed which serve as a solvent for stone and aid in disintegration.

Heat.—Even atmospheric heat causing great temperature variations of elements of building stone has a somewhat unsuspected influence. Investigations have shown that rock expanding under such conditions does not fully contract when the temperature is dropped. This lack of recovery results in a swelling which induces internal stresses and aids in disintegration of the stone.

Freezing.—Water absorbed in rock is necessarily subjected to freezing in cold climates. In the process of freezing, the water of course expands and thereby exerts great disruptive forces.

Abrasion.—The effects of friction in producing abrasion are too apparent to need discussion here, but in many places sand-laden wind causes very noticeable effects in a surprisingly short time.

Honing and Rescouring.—Stone when first quarried holds a considerable amount of water. This water carries in solution more or less of the natural cementing material of the rock. When the moisture is drawn to the surface by capillary action it deposits its mineral burden, through the process of evaporation, and thereby produces a sort of protective coating. If because of discolorations, etc., the stone surface is honed or rescoured, this protective coating is removed and destruction becomes more rapid.

Life.—The life of building stone is understood to mean the length of time that will elapse before the structure made from it will discolor or disintegrate to such an extent as to require repair.

Dr. A. A. Julien has prepared Table 5, which shows the estimated life of building stones in structures of New York City.

Weatherproof coating of boiled linseed oil, paraffin, soap, and alum may be applied with some effect if the surface is clean and dry. Ransome's process consists of filling the pores with potassium or sodium silicate, followed by calcium chloride, forming a strong lime silicate cement on the surface.

TABLE 5. ESTIMATED LIFE OF BUILDING STONES IN STRUCTURES IN NEW YORK CITY

Coarse brownstone	5 to 15 years
Fine laminated brownstone	20 to 50 years
Compact brownstone	100 to 200 years
Bluestone (sandstone)	Untried, probably centuries
Nova Scotia sandstone	Untried, perhaps 50 to 200 years
Ohio sandstone (best siliceous variety)	Probably from one to many centuries
Coarse fossiliferous limestone	20 to 40 years
Coarse dolomitic marble	40 years
Fine dolomitic marble	60 to 80 years
Fine-grained marble	50 to 100 years
Granite	75 to 200 years
Quartzite	75 to 200 years
Gneiss	50 years to many centuries

Granite.—Granite is a completely crystalline igneous rock, whose essential minerals are quartz and orthoclase feldspar, usually with mica or hornblende. (See Figures 51 and 52.)

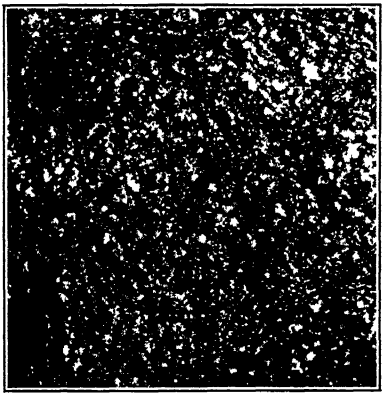


Figure 51. Fine-Grained Gray Granite, Barre, Vt.

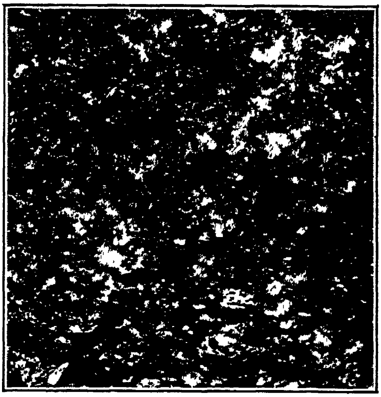


Figure 52. Coarse-Grained Granite, Vinal Haven, Maine—Gray with Pink Tinge

(Samples from Dept. of Geology, Harvard University)

Granites are named according to coarseness of grain, color, and mineral content; viz., coarse-grained micaceous red granite or fine-grained hornblendic gray granite. If prominent crystals of large size appear imbedded in a finer matrix, the texture is called porphyritic.

Most valuable granites are gray or red, but green and black, and sometimes green stones are in use. The color of the feldspar is responsible for the appearance of the lighter rocks, whereas the biotite mica, hornblende, augite, and chlorite color the darker varieties.

Granite occurs in heavy sheets. It splits easily along the *rift*, which is generally parallel to the surface of the sheet, splits fairly easily along the *grain*, which is in a certain plane perpendicular to the rift, but it splits with difficulty along the *head* or *cut-off*, which is at right angles to both the rift and grain.

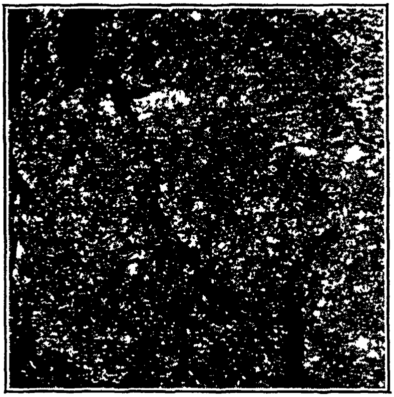


Figure 53. Gneiss, Northfield, Mass.—Gray with Black Spots and Pale Yellow Bands

(Sample from Dept. of Geology, Harvard University)

The finer-grained, light-colored granites are desirable for building construction; the darker ones for monumental and decorative work. Granite is used for trimming and curbing, and the coarser-grained varieties are often crushed and used for permanent road material, although they are inferior to some of the basic irruptives for this purpose.

Gneiss.—Gneiss is a rock with the same mineralogical composition as granite from which it has been metamorphosed into a laminated condition. (See Figure 53.)

Trap Rock.—Trap rock includes various dense, heavy, igneous rocks, dark in color, which due to rapid cooling, are very fine-grained. They include basalt, diabase, fine-grained gabbros, and some fine-grained diorites. They are not used much for building construction because of great difficulty in quarrying, but they make good aggregate for concrete, and excellent road building material, where a certain cementing quality with high resistance to abrasion is desirable.

Limestone.—Technically, limestone is understood to mean a rock mass consisting essentially of calcium carbonate, $CaCO_3$, or of a mixture of calcium carbonate and magnesium carbonate, $MgCO_3$. (See Figures 54 and 55.)

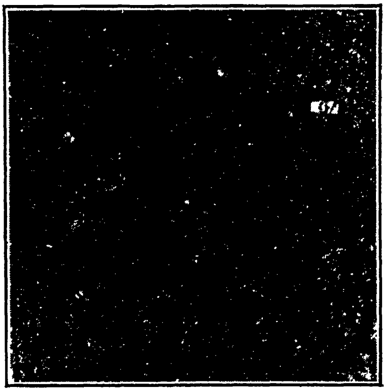


Figure 54. Coarse Limestone, Lockport, New York—Gray in Color

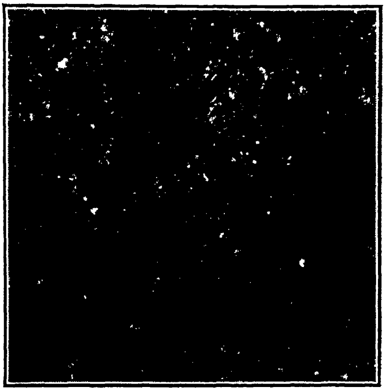


Figure 55. Encrinal Limestone, Lockport, New York—Red, Gray, and Brown

(Samples from Dept. of Geology, Harvard University)

Limestone containing 15% to 40% of magnesium carbonate is called *magnesian limestone* and when the percentages of calcium and magnesium carbonate are about equal the term *dolomite* is used.

Marble.—Geologically, marble is a metamorphosed limestone; it is more crystalline, coarser grained, more compact, and purer in color. Commercially, the term marble is applied to any limestone capable of taking a polish.

The texture of marble varies from soft, friable, fine-grained chalk, to crystalline and compact types.

Limestones, dolomites, and marbles are the result of various kinds of formation processes. The primary source is from the lime dissolved from igneous rock as they are decomposed by carbonaceous waters. These waters either deposit the lime in various forms, such as some form of travertine or as a cement in other rocks; or the lime is consumed by living organisms, later to occur as calcareous deposits as the organisms die. Impurities deposited at the same time modify the appearance of the resulting rock to a very great extent. (See Figures 56, 57, 58, and 59.)

Limestone is porous and many changes occur in it after original formation, by infiltration of impurities. Limestones vary greatly in hardness with a maximum of about 3.

Limestones and marbles are relatively easy to quarry by use of channelers, or by drilling, and wedging. After the blocks are taken from the quarry they are readily sawed into slabs, blocks, or sheets.

Limestones and marbles may be finished by sawing, hammering, or polishing. There is one item about polishing that deserves attention, as follows. The final polishing operation is accomplished by the use of diatomaceous earth and putty or oxalic acid. The use of oxalic acid reduces the time and expense, but the life of the surface is very short. It is much more desirable to leave the finish produced without the use of the acid.

Use of Limestone and Marble.—A great deal of limestone is used in the production of lime for structural work and various industrial processes. Limestones of fine uniform texture and color are used in building construction.

Marbles are used for structural and monumental work.

Figure 56. St. Beaume Marble, Province of Var, France—Yellow and White with Red Lines

Figure 57. Porphyritic Marble, Vitulano, Italy—Gray and White

(Samples from Dept. of Geology, Harvard University)

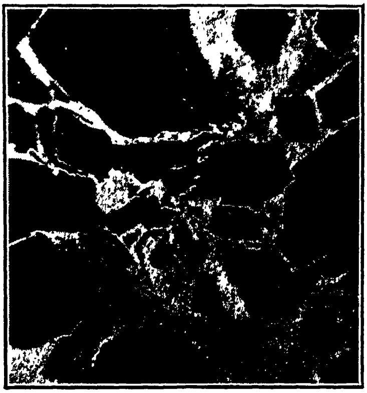


Figure 58. "Black and Gold" Marble or Porto from Porto Venere near Spezia, Italy

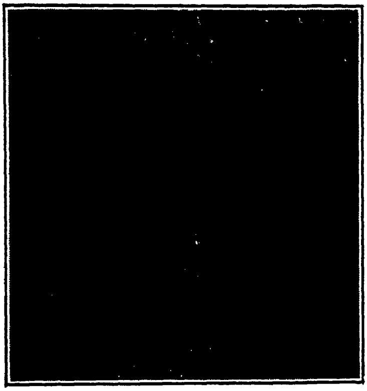


Figure 59. Dark Tennessee Marble—Brown and White

(Samples from Dept. of Geology, Harvard University)

They are largely used for decorative work in ornaments, fittings and fixtures. Serpentine (Figure 62) is often used as a substitute for marble.

Sandstones.—Sandstones consist essentially of quartz grains cemented together by lime, silica, clay, hydrous or anhydrous oxide of iron, gypsum, calcium phosphate, or bituminous compounds. The color of these stones is largely determined by the color of the cements, modified by the sand grains themselves. (See Figures 60 and 61.)

The quarrying of sandstones varies with the type of rock encountered. Channeling and blasting are used, but the blasting operations always result in the loss of some material. Cracks started by blasting sometimes do not show until some time after the blocks have been set in structural position.

Sandstones are used for a great many structural purposes, for many of them are wonderfully resistant to weathering. Some of the uses are as follows: building construction, including bridges, dams, etc., for general stone work as well as for trim; road construction, including paving blocks, macadam, and crushed rock, and many other miscellaneous uses.

Shale and Slate.—Shale is formed by the consolidation of a mud or clay. It is laminated in structure, tending to form in more or less imperfect sheets. Obviously, there may be as many kinds of shale as there are muds or clays from which they are formed. The cementing material between the flour-like particles is of minor importance because the coherence of the shale is primarily due to the pressure exerted on the particles contained in the mud and clay. Shale is not of much commercial importance. It is used to some extent as road material and for cement and brick manufacture. It is the source of many oils.

Slate.—"Slate is a metamorphosed clay or shale." In commercial parlance it denotes rock which will split more or

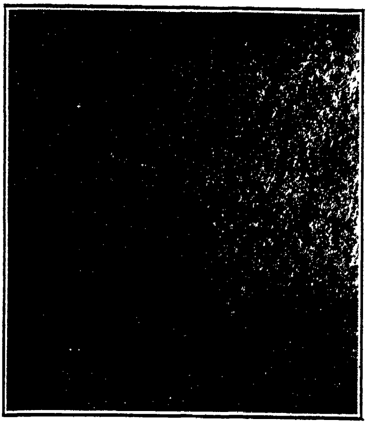


Figure 60. Pink Sandstone, Potsdam, New York

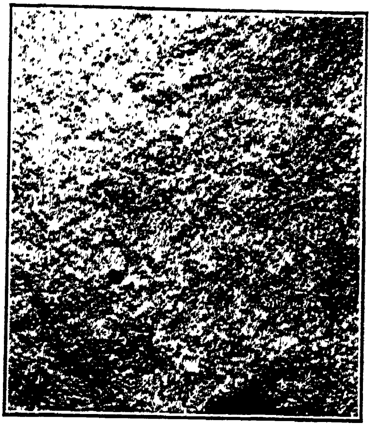


Figure 61. "Brownstone" Sandstone, Portland, Conn.

(Samples from Dept. of Geology, Harvard University)

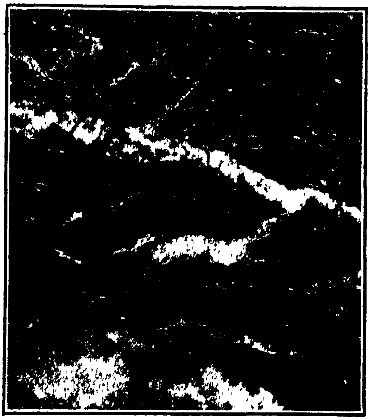


Figure 62. Serpentine, New York State—Dark Green and White

(Sample from Dept. of Geology, Harvard University) less easily into comparatively thin, perfect sheets. It is a very fine-grained material, produced by enormous pressure to induce the slaty cleavage. Clay slates have low strength and elasticity while the so-called mica slates are much stronger and more elastic.

Color is one of the most important characteristics of slate, especially for roofing purposes. It should be noted that most slates either change color or fade upon prolonged exposure to the elements.

The texture of slate varies greatly, some being very fine and some coarse. For roofing slate, a tough, strong, elastic material is desired; one especially which will not easily fracture when the nail holes are punched.

The uses of slate are quite numerous, but various well-known non-fading, colored slates are much used for roofing. Slate is also used for floor and stair treads, blackboards, billiard tables, etc. Certain slates low in magnetite content are very desirable for electrical switch boards.

The transverse strength of slates is an important item, and

TABLE 6. PHYSICAL PROPERTIES OF STONE COLLECTED FROM VARIOUS SOURCES

Kind of Stone	Locality	Compressive Strength lb. per sq. in.	Modulus of Rupture lb. per sq. in.	Shearing Strength lb. per sq. in.	Modulus of Elasticity lb. per sq. in.
Granite...........	Troy, N. H.	26,200	2,170	2,206	4,545,000
Granite (pink).....	Milford, Mass.	19,000	....	1,800	5,128,000
Granite...........	Branford, Conn.	15,700	1,200	1,800	7,000,000
Limestone.........	Bedford, Ind.	10,800	1,740	1,120	7,250,000
Limestone.........	Beaver, Ark.	20,500	2,700	22,000	6,600,000
Limestone.........	Minnesota	4,500	250	1,130	....
Marble (etowole)...	Georgia	14,000	....	1,400	7,500,000
Marble (white)....	Rutland, Vt.	11,900	1,250	1,020	4,500,000
Marble (fossil).....	St. Joe, Ark.	10,300	1,600	....	10,700,000
Sandstones........	Worcester, Mass.	9,800	....	1,242	2,400,000
Sandstones........	Oregon	12,600	2,200	1,600	3,300,000
Sandstones........	Cabin Creek, Ark.	18,500	1,700	2,500	3,900,000

the modulus of rupture as determined by Mansfield Merriam ranges from about 6,500 to 11,000 lb. per sq. in.

Reference

Richardson, C. H. "Building Stones and Clays." Orange Publishing Company.

CHAPTER 7

FERROUS METALS

Pig Iron.—The crudest form of iron, or the raw material from which the others are finally produced, is pig iron. Knowledge of the characteristics of this material is therefore quite essential.

Production of Pig Iron.—Pig iron is obtained as the product of reduction of iron ore in the blast furnace. (See Figure 63.) All of the material of the furnace charge is introduced at the top through a special "gas lock" hopper. (See Figure 64.) The essentials of the charge are ore, fuel, and flux.

The ore may be of various kinds, but red hematite is the most common. For the fuel, coke is almost universal. The flux is limestone which is used to combine with the impurities and form a liquid slag.

The product of the blast furnace is called pig iron whether it is melted or cast into pigs. When the iron is cast into pigs in sand molds, it is called "sand pig." "Machine pig" is cast in metal molds in a continuous casting machine.

In the manufacture of steel, the raw pig iron is often transferred to the steel furnaces in the melted state to conserve heat.

Grades of Pig Iron.—Pig iron is produced under circumstances which cannot prevent the association of various other elements. The most important of these elements are carbon, silicon, sulphur, phosphorus, and manganese.

There is so much carbon in the fuel that the iron is practically saturated with it, and the carbon content is fairly constant at 3.5% to 4%. Various grades of pig iron are recognized in the trade as listed in Table 7.

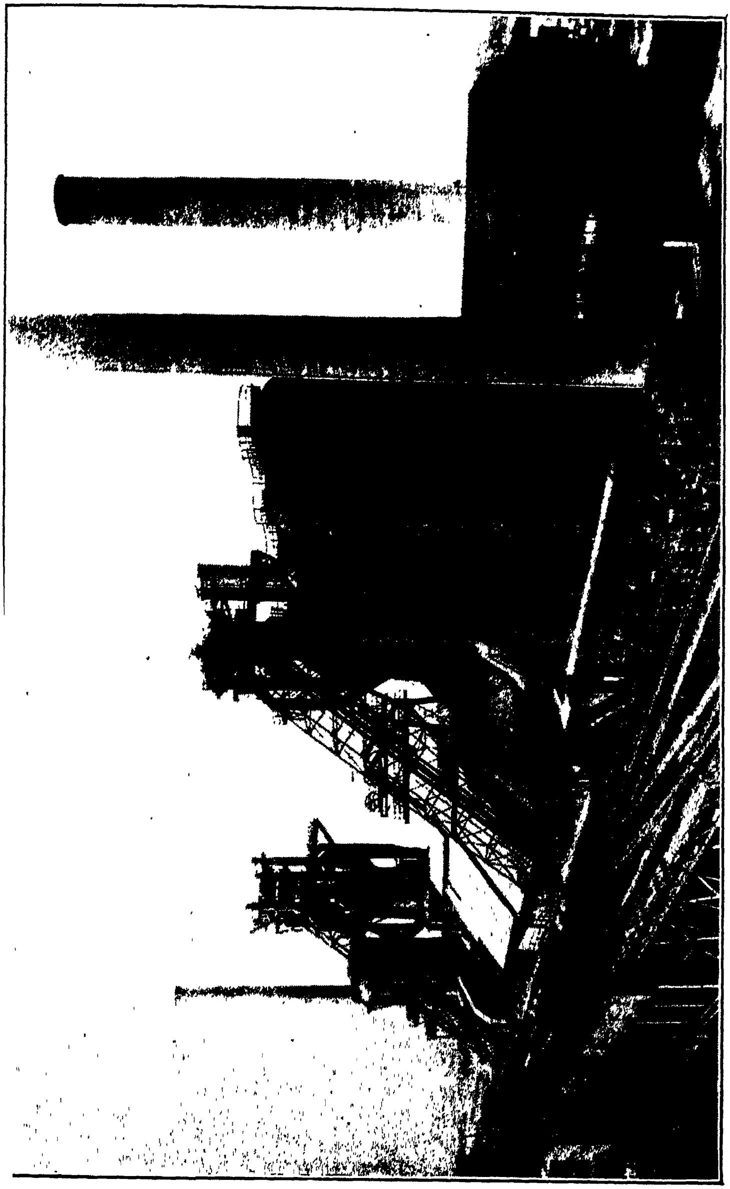
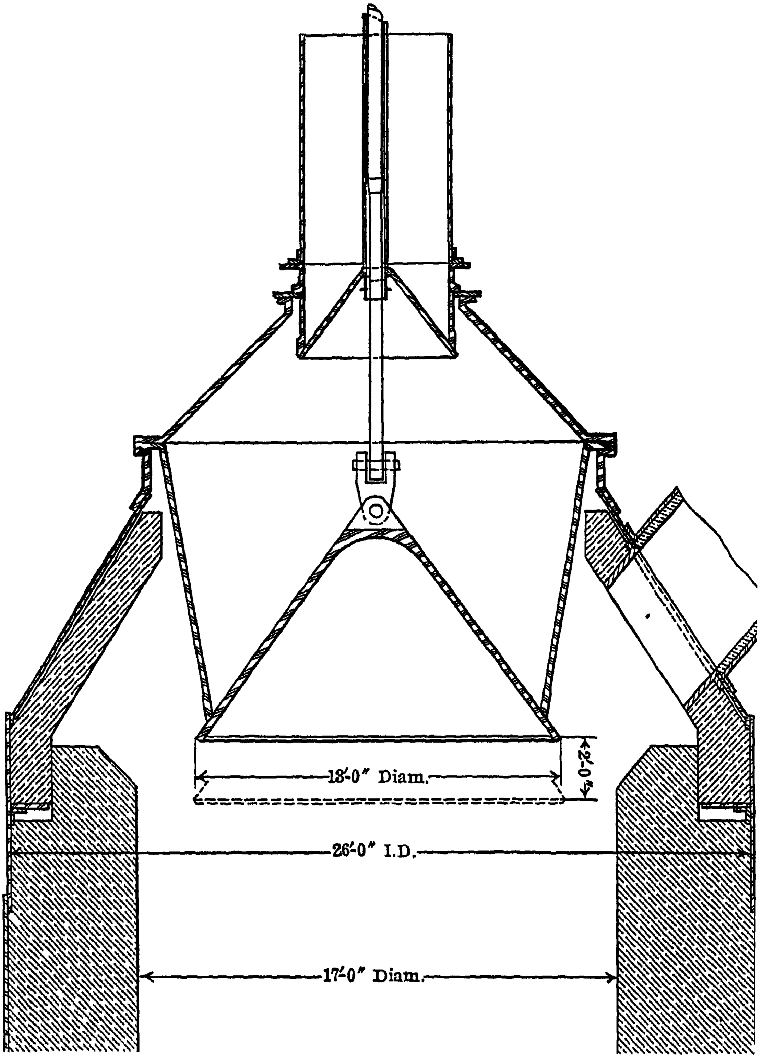


Figure 63. Blast Furnaces at St. Louis Coke & Iron Corp.

(Courtesy of Riter-Conley Co.)


13'-0" Diam.
2'-0"
26'-0" I.D.
17'-0" Diam.

(Courtesy of Riter-Conley Co.)

Figure 64. Gas Lock Hopper at Top of Blast Furnace for Introduction
Raw Material

TABLE 7. GRADES OF PIG IRON

	Carbon Content 3.5% to 4%			
	Si	S	P	Mn
No. 1 Foundry	2–3	<0.035	0.5–1.0	<1.0
No. 2 Foundry	2–2.5	<0.045	0.5–1.0	<1.0
No. 3 Foundry	1.5–2.0	<0.055	0.5–1.0	<1.0
Gray Forge	<1.5	<0.100	<1.00	<1.0
Malleable Bessemer	0.75–1.50	<0.050	<0.20	<1.0
Bessemer	1–2	<1.05	<0.10	<1.0
Basic	<1	<0.05	<1.0	<1.0
Basic Bessemer	<1	<0.05	2–3	<1–2

Foundry irons are intended for the manufacture of iron castings. Softness and soundness are desired with reasonable strength.

Silicon. Increasing the silicon content promotes the formation of graphitic carbon and thus tends to increase softness.

Sulphur. Sulphur promotes the formation of combined carbon and tends to increase hardness.

Phosphorus. High phosphorus decreases strength but increases fluidity and therefore is of value in the manufacture of thin castings, stove plate, etc.

Foundry irons are of higher grade (and value) with increasing silicon and decreasing sulphur content.

Gray forge iron is a lower grade of foundry pig often used in the puddling furnace for manufacture of wrought iron.

Malleable Bessemer pig iron is intended for the production of malleable cast iron. Silicon is held within restricted limits to ensure hard, white castings which will subsequently be converted to the proper soft gray texture by annealing. Phosphorus is kept low because of strength considerations, but not too low to destroy fluidity in casting.

Bessemer pig iron has a silicon content sufficiently high for the requirements of the acid Bessemer steel-making process.

Phosphorus must be below the limiting amount for a satisfactory steel since it is not removed by the acid process.

Basic pig irons are intended for steel-making by basic processes in which phosphorus can be removed. Economic slag conditions necessitate low silicon. In the basic Bessemer process, high phosphorus is needed for its fuel value; it is not essential in the open hearth process.

Cast Iron.—Cast iron is remelted pig iron of various grades mixed together, and generally with a certain proportion of carefully selected scrap. A very close control of the silicon, especially, is possible and an iron may be obtained suitable for light or heavy castings, or for open or close grain as may be desired.

Variations in Cast Irons.—Cast irons vary widely in their characteristics. Several reasons for such variations are as follows:

1. The rate of cooling, which in most cases is slower as the section becomes heavier.
2. The chemical composition of the iron.
3. The pressure under which the cooling takes place.

Effect of Rate of Cooling.—Rapid cooling tends to produce fine-grained material and tends to retain the carbon in the combined state and render the material hard. Slow cooling has the opposite effect.

Effect of Chemical Composition.—As already stated, the most important elements affecting pig iron are carbon, silicon, sulphur, and phosphorus. Manganese should also be included although it is generally low enough so as not to bother.

Carbon. The presence of graphitic (free) carbon makes castings soft, while combined carbon makes them hard (white iron).

Silicon in small percentages increases the fluidity of molten iron, decreases blow holes, and increases the density of castings. It also reduces the solubility of carbon in iron so that it promotes the decomposition of the hard carbide into soft carbonless iron and graphite, thereby acting as a softener. It also tends to reduce shrinkage.

The accompanying reproductions of micrographs (Figure 65) show something of the effect of silicon.

Sulphur is undesirable and should be limited to less than 0.1%. It is believed to promote the formation of combined carbon and is sometimes increased for metal cast in chills. The sulphur combines with the manganese to make manganese sulphide, MnS, or with the iron, if there is not sufficient manganese present to satisfy it, to make FeS. These sulphides solidify at a rather low temperature and tend to make the castings very brittle just below the solidification temperature. Castings are therefore very liable to crack badly in cooling. The effects of sulphur may be somewhat neutralized by proper additions of silicon.

1.75% silicon. Breaking strength of arbitration bar 3,860 lb.

2.5% silicon. Breaking strength of arbitration bar 3,600 lb.

3.5% silicon. Breaking strength of arbitration bar 2,500 lb.

Figure 65. Section of Gray Cast Iron
Original magnification 100 times—unetched

Phosphorus up to 0.5% has no marked effect on cast iron. If more than 2% is present, the iron becomes brittle and the strength is diminished. However, high phosphorus irons are very liquid when melted and are therefore used when it is necessary to pour very thin castings.

Manganese increases the solubility of carbon in iron and opposes the formation of graphite, thereby making a hard iron.

It also increases the shrinkage. It should not be in excess of the amount necessary to satisfy the sulphur. In general, it should be low for an iron to have good machining qualities.

No All-Around Good Iron.—From the above discussion it is easy to see that no one iron mixture will satisfy the requirements for castings of both heavy and light sections.

Defects.—There are many defects which appear in iron castings: checks, segregation, blow holes, coarse or open grain, spongy spots, and "cold shuts."

Checks generally occur on account of errors in design resulting in unequal rates of cooling and introduction of high shrinkage stresses.

Segregation is generally very pronounced in high phosphorus irons and occurs in the parts which solidify last. Sulphur is often high in such areas. Sometimes carbon and silicon segregate in such a way that some parts of a casting are hard and other parts soft. Such castings are very hard to machine.

Blow holes are generally due to improper venting.

Coarse grain is caused by too slow cooling.

Spongy spots are caused from lack of "feeding" or from improper "risers."

"Cold shuts" arise from cold material or from improper gating.

"Kisle," excess of graphitic carbon caused by too high carbon content, appears as soft, brownish spots.

Physical Properties of Cast Iron.—Cast iron finds its greatest use in construction of heavy machine frames where the mass is of far greater importance than the strength. In such cases the prime requisite is soundness and machinability. A considerable amount of iron is used for pipes, valves, and fittings requiring a fine-grained, dense material of high strength, and fair degree of machinability. Many other special applications require strength, density, and machinability in different degrees.

Hardness.—Recognizing that machinability is very important, Keep has invented a special drill designed to measure the resistance to penetration in drilling.

The drill is a straight, fluted, $\frac{3}{8}$-in. drill pointed upward and rotated at 200 r.p.m. The sample is pressed against it with a pressure of 150 lb. An autographic record shows the rate of penetration of the drill. A slope of the curve of the diagram of 0° means that the penetration is infinite, while 90° means no penetration. (See Figure 66.)

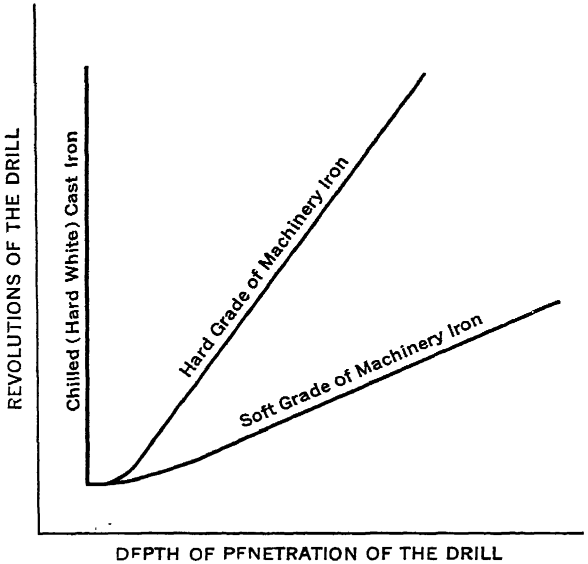


Figure 66. Typical Diagrams from Keep Drill Test for Hardness in the Sense of Machinability as Applied to Cast Irons

With this device the hardness of white iron is 90° while machinery iron will vary from 25° to 50°. The *Brinell hardness* will vary from 90 for soft irons up to 200 for dense, strong irons, while white iron will vary from 380 to 500.

Tensile Strength.—Cast iron is comparatively weak in tension and little is generally expected of it used in that way. Nevertheless, tension tests are valuable as indicating the quality of the iron.

The size of the bar from which the test plug is taken exerts a marked influence on the strength and should always be considered. Samples from large bars will, in general, give lower strengths than those from small bars.

The tenacity of gray iron ranges from 12,000 lb. per sq. in. for soft, coarse-grained irons to 35,000 lb. per sq. in. for hard, close-grained irons. Results have been reported as high as 45,000 lb. per sq. in., but these are uncommon.

Hard, white irons may vary from 40,000 to 70,000 lb. per sq. in., depending on the section.

The modulus of elasticity of cast irons varies considerably. Ordinary gray irons will have a modulus of 12,000,000 to 15,000,000 lb. per sq. in., while very strong irons will sometimes have a modulus as high as 20,000,000 lb. per sq. in. or a little over.

Compressive Strength.—Cast iron is remarkably strong in its resistance to crushing and it is this property that makes it so valuable in building construction. Roughly, the crushing strength is about five times the tensile strength. Thus a fairly close estimate of the crushing strength may be made if the tensile stress is known.

Compressive strength will vary from about 35,000 lb. per sq. in. for soft, open-grained castings, to about 200,000 lb. per sq. in. for dense, close-grained, gray iron.

The white irons are very hard and strong in compression. The compressive strength is often as high as 250,000 or 275,000 lb. per sq. in.

Strength of Columns.—Although the compressive strength of small samples of cast iron is rather high, columns made of this material show a relatively low strength. For example, specimens 10.5 in. long and only 1 sq. in. cross-section, when tested as columns, failed in triple flexure at an average stress of 63,000 lb. per sq. in.; but full-size columns (hollow) made of the same material showed not more than half that strength, and the actual stresses obtained agreed very well with the formula, stress at breaking load, $p = 34{,}000 - 88\frac{l}{r}$. All cast iron pipes and columns should be carefully calipered in order that variations in the wall thickness due to shifting of the cores may be detected. Careful inspection for blow holes and segregation should be insisted upon.

Centrifugally Cast Pipe.—A few foundries equipped with special machinery are manufacturing cast iron pipe by the "centrifugal" method. The iron is poured while the mold is rotated rapidly and it is thereby possible to produce a dense, strong, iron pipe with uniform wall thickness, without the use of cores. An increasing amount of pipe is being manufactured by this method each year.

Transverse Strength of Cast Iron.—Transverse tests are preferred by foundry men to any other mechanical tests. The specimens are easily and quickly prepared, and are inexpensive because they require no machining. A simple and inexpensive testing machine, readily operated by inexperienced men, gives sufficiently accurate results of both strength and toughness.

The standard test bar called the "arbitration bar" is commonly used. It is a cylindrical bar, 1¼ in. in diameter, and 15 in. in length. The load is applied at the center of a 12-in. span. (See standard specifications of A. S. T. M.)

The load itself is considered as the measure of the strength of the bar, although the modulus of rupture must be calculated for comparsion with other shapes. An approximate measure of the toughness may be calculated by multiplying the load by one-half the center deflection at the time of rupture, giving a rough estimate of the energy rupture.

The modulus of rupture varies from 1.5 to 2.25 times the tensile strength, depending somewhat on the toughness of the material.

In order to pass the standard specification for gray iron, the arbitration bar must have a deflection at the center of a 12-in. span of at least 0.1 in. and the minimum center loads should be 2,500, 2,900, and 3,300 for light, medium, and heavy castings respectively. These loads, taken together with the deflection, are equivalent to a demand for energies of rupture of 8.5, 9.8, and 11.2 in lb. per cu. in. Good gray iron of round or square cross-section of 1½ sq. in. in area should have a modulus of rupture of at least 45,000 lb. per sq. in.

Shearing Strength of Cast Iron.—Comparatively short blocks of cast iron tested in compression fail in shear (see Figure 4); and bars tested in torsion (pure shear) fail in tension (see Figure 6b). It is quite apparent then that the shearing strength lies between the compressive and the tensile strength. An examination of the published results seems to indicate that the shearing strength is about 10% to 15% above the tensile strength.

When cast iron is used for structural members, each piece should be subjected to rigid inspection, and stresses should be kept low. Shrinkage stresses, cleavage planes (due to the crystal formation on cooling) and various other influences make cast iron a rather treacherous material for important structural members.

Shrinkage Stresses.—During cooling, especially after crystallization takes place, cast irons are subject to great shrinkage and if not properly provided for, this causes considerable strain and stress; enough to produce rupture. The heavier and thicker the castings, the greater the temperature gradient between the outside and inside and the greater these shrinkage stresses become.

Seasoning of Cast Iron.—If castings are allowed to "season" for several months before final machining operations are made, the bad effects of warping may often be obviated. When castings are machined the shrinkage stresses are partly relieved and the castings are prone to warp. The long-time seasoning permits some internal physical readjustments which relieve most of the internal stresses so that the final machining may be much more accurately accomplished. Many concerns take advantage of this seasoning effect and partly machine important castings after which they put them aside until it is necessary to complete the processes.

Swelling of Cast Iron on Reheating.—It is a well-known fact that cast irons, especially those having high silicon and graphite content, will swell considerably when heated repeatedly between 1,400° and 1,600° F. Castings which are slightly undersize have been salvaged in this manner, but such practice must be carefully done and if carried too far the material becomes weakened and finally cracks. When it is necessary to use cast iron where it is subject to repeated heating, trouble can be greatly reduced by using fine-grained, gray iron very low in graphite. Steel is a preferable material for such practice, however.

EXTRACTS FROM STANDARD SPECIFICATIONS OF AMERICAN SOCIETY FOR TESTING MATERIALS FOR GRAY IRON CASTINGS[1]

1. These specifications cover three classes of gray iron castings as follows:

(a) *Light Castings*—those having any section less than ½ in. in thickness.

(b) *Heavy Castings*—those in which no section is less than 2 in. in thickness.

(c) *Medium Castings*—those not included in either of the other two classes.

2. The tension test shall be made only when specified by the purchaser, and at his expense. (Recommended by the committee that this

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[1] See standard specifications of A. S. T. M. for complete discussion.

test shall not be made, for the reason that cast iron is very brittle and hence any deviation from an absolutely straight pull in commercial testing machines yields defective results.)

3. Castings shall be made by the cupola process unless furnace iron is specified.

4. Chemical Composition. Drillings taken from fracture ends of test bars shall conform to the following requirements as to sulphur:

Light castings	not over 0.10%
Medium castings	" " 0.10%
Heavy castings	" " 0.12%

5. (a) Transverse test specimens (arbitration bars). Centrally loaded on supports 12 in. apart.

	Class of Casting			Special High-Test
	Light	Medium	Heavy	Gray Iron
Load at center—lb.	2,500	2,900	3,300	3,800
Deflection at center—in.	0.10	0.10	0.10	0.12

(b) The rate of application of load shall be such that a central deflection of 0.10 in. is produced in from 20 to 40 seconds.

6. When tension tests are specified the specimens shall be turned from the broken ends of the transverse test specimens and shall conform to the following minimum requirements as to tensile strength:

Light castings	18,000 lb. per sq. in.
Medium castings	21,000 " " " "
Heavy castings	24,000 " " " "
High-test gray iron castings	28,000 " " " "

Malleable Cast Iron (Annealed Special White Iron)

Raw Castings.—When pig iron of the following composition—silicon 1.00 to 1.50, manganese 0.60, phosphorus 0.225, and sulphur 0.05%—is melted carefully in an air furnace, an open hearth or electric furnace and the molten material is then poured in suitable molds which cause quick cooling, a white iron is produced. (See Figure 67.) The average total carbon is about 3.04 %, but it varies from about 2.85% to 3.30%. Of this amount the combined carbon averages about 90%.

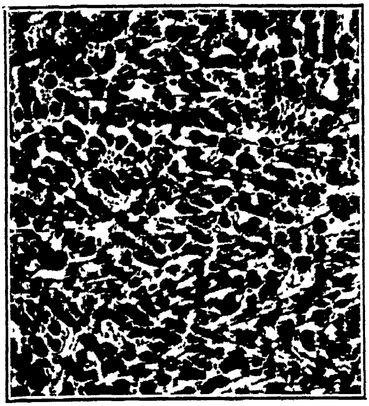
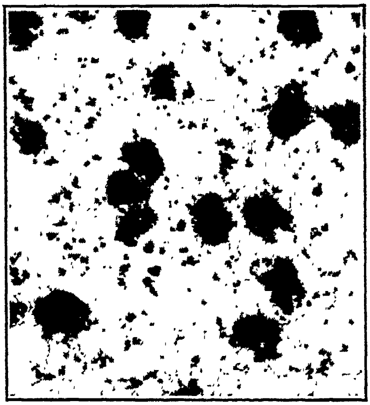


Figure 67. Section of White Iron
Original magnification 100 times



(Courtesy of E. Touceda)

Figure 68. Annealed Iron: Normal Structure Showing Temper Carbon
Original magnification 100 times

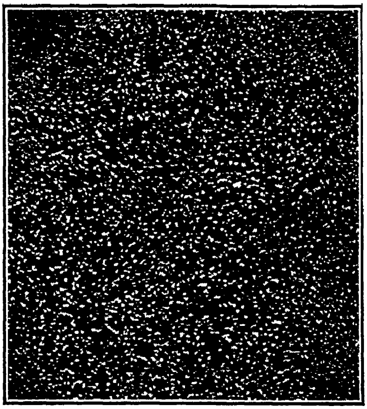
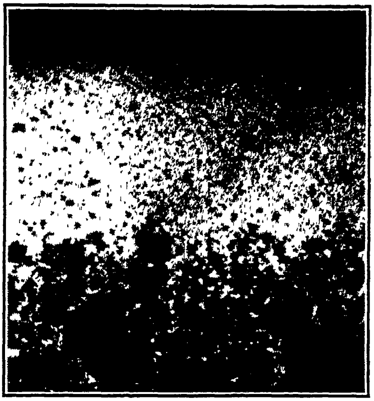


Figure 69. Annealed Iron: Showing Uniform Distribution of Temper Carbon
Original magnification 8 times



(Courtesy of E. Touceda)

Figure 70. Annealed Iron Showing Decarbonized Border, Pearlite Underneath
Original magnification 100 times

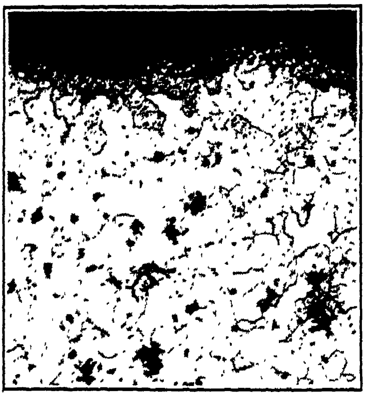
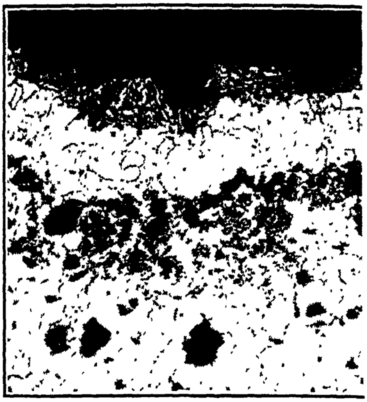


Figure 71. Faulty Anneal of Iron: Pearlitic Border. Hard to Machine
Original magnification 100 times



(Courtesy of E. Touceda

Figure 72. Faulty Anneal of Iron: Cementitic and Pearlitic Outside. Ring of Ferrite Overlying Pearlite
Original magnification 100 times

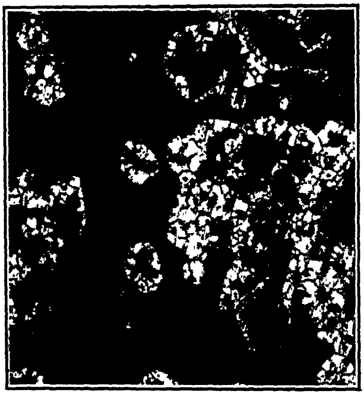
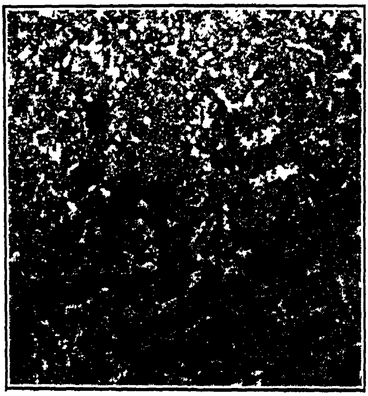


Figure 73. Annealed Iron Showing Effect of too Quick Cooling from the Annealing Temperature
Original magnification 100 times



(Courtesy of E. Touceda)

Figure 74. Poor Anneal of Iron. Either Time or Temperature Not Sufficient to Break up the Hard Carbide of the Original White Iron
Original magnification 100 times

Annealing.—Castings of this character are carefully packed in rectangular boxes 16 in. by 24 in. by 12 in. high. The packing material is generally mill scale and siliceous slag, or hematite and pulverized magnetic ore. Above all it is important that this packing be porous to allow the penetration of CO_2 (carbon dioxide gas) generated in the furnace. The boxes or "saggars" are stacked four deep in an annealing furnace and heated slowly to 1,300 to 1,500° F. The temperature is held at this range for from 60 to 72 hours and then the castings are very slowly cooled until well below the critical temperature.

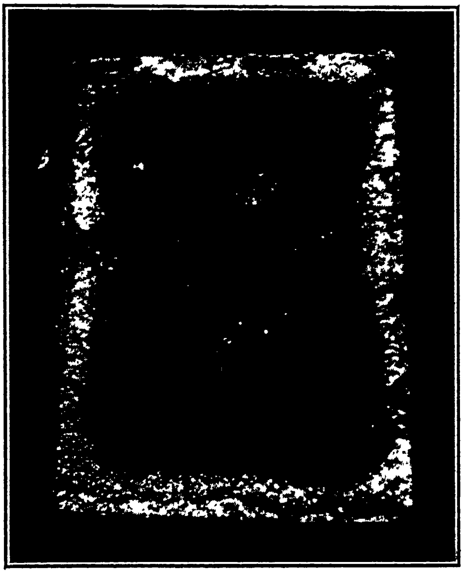


Figure 75. "Picture Frame Fracture" Black Heart Malleable Iron
Original magnification 2½ times

Black Heart and White Heart.—When annealing covers a period of about five days at the temperatures as stated above, the combined carbon is changed to a special type of graphitic carbon called temper carbon, of finer, more rounded, and more uniformly disseminated grains than the graphite of gray iron. (See Figures 68 to 74.)

The strongly oxidizing nature of the gases in the process causes a practically complete decarbonization of the outside of the castings. The cross-section of a fractured section reveals a white shell and a black core; the typical "picture frame" fracture of "black heart" malleable iron. (See Figure 75.)

When the temperature of annealing is considerably higher and the period of heating considerably longer, there is a greater reduction in the total carbon and a much thicker shell of decarbonized iron. A coarse-grained, somewhat less strong casting called "white heart" results.

"Black heart" is the most common American product, but "white heart" is more common in European practice.

Table 8 gives the chemical composition and physical properties of "black heart" iron:

TABLE 8. COMPOSITION AND PROPERTIES OF "BLACK HEART" IRON
(Annealed 108 hours)

	Before Annealing	After Annealing	Loss	Gain
Total carbon	3.04	2.66	0.38	
Combined carbon	2.85	0.31	2.54	
Graphitic carbon	0.19	2.35		2.16
Manganese	0.21	0.21		
Silicon	0.73	0.72	0.01	
Phosphorus	0.154	0.153	0.01	
Sulphur	0.500	0.500		

TENSILE TESTS OF ANNEALED SPECIMENS

	Av.	High	Low
Tensile strength	49,810	69,100	38,900
Per cent reduction	6.23	9.8	1.3
Per cent elongation	6.61	10.3	2.8

Average from 42 tests
All annealed 108 hours

These tests show the range of properties possible. It is quite possible to get a considerable toughness under the rigid conditions of production.

Improvement in Malleable Iron.—The following paragraphs on malleable iron were prepared for this book by Enrique Touceda, Consulting Engineer for the Malleable Iron Research Institute.

"Owing to the fact that it is only within a comparatively few years that a scientific study of the metallurgy of malleable iron was undertaken, and the melting and heat-treating apparatus, and operations brought to a high degree of perfection, the average engineer has lacked the opportunity of following such progress as has been made to the same degree as would obtain in the case of other ferrous and non-ferrous metals. This is particularly true as the literature on the subject has been of a more or less fragmentary character, being contained in the transactions of technical societies and the publication of the technical press. In most of these articles the metallurgy of the process has been given prominence, while the characteristic merits of castings in the various fields have received but scant attention. The result has been that the engineer has been prejudiced against the product because of the belief that the present-day product is in no sense superior to the character and quality of castings that were sold in the old days when they were deficient both in uniformity and in strength.

"To make clear the length to which present-day improvement and control have been carried, the case is rare where an analysis of each heat is not made, while in many cases preliminary analysis is made of metal withdrawn from the furnace during the progress of the heat, in order that it can be ascertained whether corrections are necessary prior to the tapping of the metal, and to insure the uniformity of one heat with another. Tensile and impact tests are made from all heats, and the melting, and heat-treatment operations under pyrometric control, are carried out with exactness and painstaking refinement not excelled in any other metallurgical industry.

"In the case of some 60 plants, the test bar results are tabulated monthly. As the American Society for Testing Materials is looked upon as the clearing house for specifications in general use, the product is guaranteed to be equal to or better than would be covered by their requirements, but the case is exceptional indeed when it is not far superior to it.

"This specification (A-47) is based upon the use of a tensile test bar 7½ in. long; a 2½-in. gauge length of ⅝ in. in diameter; the grip ends being 2½ in. long by ¾ in. in diameter.

A. S. T. M. MINIMUM REQUIREMENTS (A-47)

Ultimate strength..........	50,000 lb. per sq. in.
Yield point...........	30,000 lb. per sq. in.
Elongation in 2 in...........	10.00%

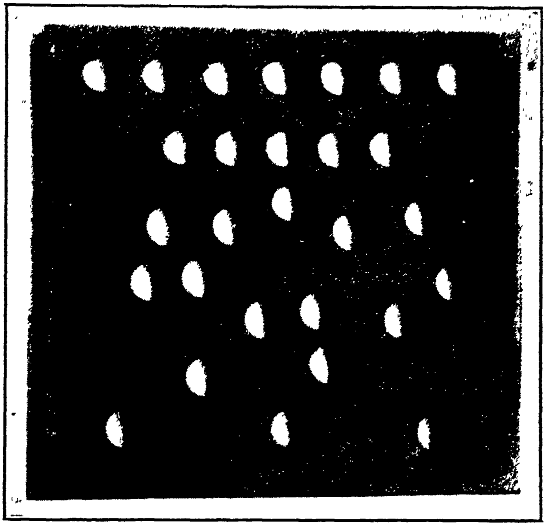
"The mechanical characteristics of the product that will distinguish it from ordinary steel, such as is used in castings, bolts, etc., are its much higher yield point, accompanied by an elongation somewhat in excess of 17%.

"Another characteristic of importance is the ease with which malleable iron can be machined, thus permitting an increase of production by a large margin over that of any other ferrous product, except very soft gray iron. Not only is this the case, but equally important is the fine character of machined surface.

"Malleable iron can be sheared and punched with facility and the practice of punching instead of coring the holes is not unusual in certain cases, both on account of more accuracy in spacing the holes through the use of a templet, and because at times this method is cheaper. (See Figures 76 and 77.)

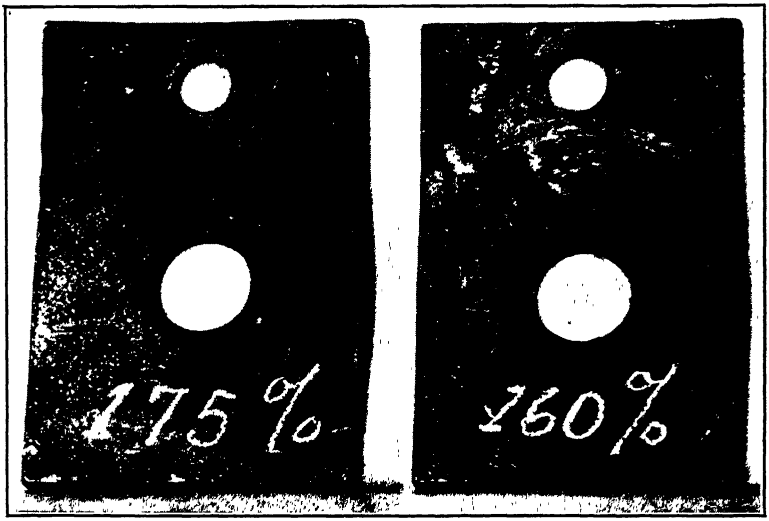
"Of equal value is the characteristic soundness and absence of blow holes. Owing to its low melting point and high degree of fluidity the amount of occluded gases in the metal as cast is comparatively small and the tendency to form blow holes consequently minimized.

"It must be borne in mind that all foundries without exception are confronted with what can be covered by the term 'molding difficulties.' Due, in many instances, to a lack of molding knowledge on the part of the engineer designer, and



(Courtesy of E. Touceda)

Figure 76. Punched Plate 5/8 in. Thick Indicates Ease with Which Malleable Iron May be Punched



(Courtesy of E. Touceda)

Figure 77. Malleable Iron Plates

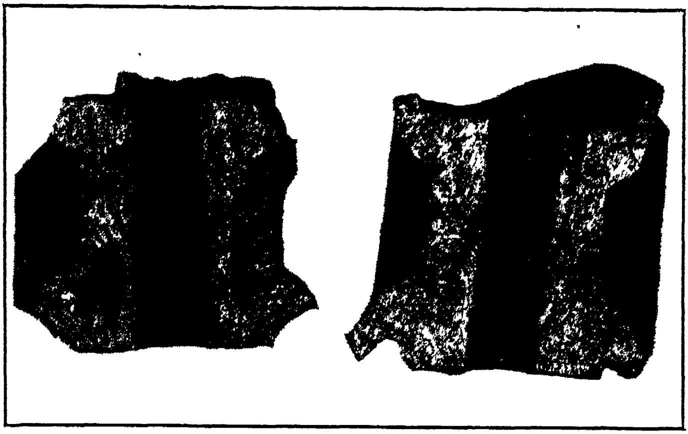
The bottom hole in each plate was originally the same size as the one at the top. A drift pin was driven in until there were indications of the start of a crack. Illustrates ductility of the product.

to the demand for castings of very intricate design involving extremely disproportionate sections, the molding problem with which the foundry is confronted is at times replete with difficulties. Briefly, shrink must be overcome through the use of gates that through trial are most advantageously placed and by the use of large risers, the function of which is not only to furnish plenty of hot metal thoroughly to feed the casting during the period of solidification, but to create a head that will deliver the metal under sufficient pressure to make sure that shrink will be absent. This in turn means that at times the weight of sprue and heads exceeds the weight of the castings, thus putting a serious burden on the cost of the casting. (See Figures 78 and 79.)

"There are a number of authentic cases in which comparative tests in service indicate that malleable iron is more resistant to corrosion than is ordinary steel.

"The metal is unsuitable for parts that are subjected to severe wearing action and it should not be used in cases where it is to be heated at a temperature in excess of 1,325°F. It cannot be successfully welded or cased.

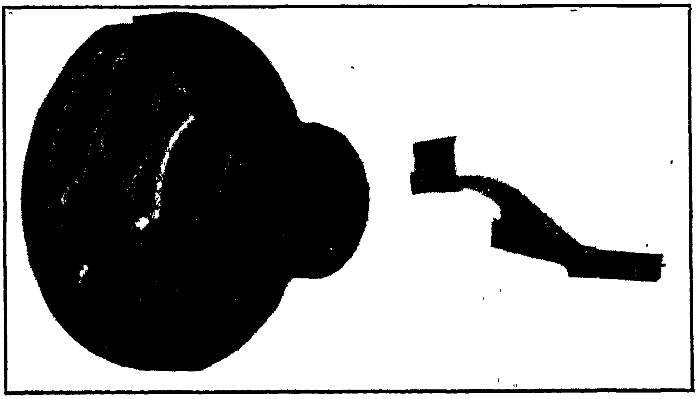
"In the purchase of malleable iron castings the first safeguard of the engineer should be to select his source of supply with care. This can be accomplished in part through an examination of the test bar record coupled with an inspection of the facilities available for proper metallurgical control. It is plain that those who are not in a position to follow through their operations in an up-to-date manner, or who are not watchful of the uniformity of their product, cannot be expected to furnish a product under the severe demand that exists today. The source of supply being safeguarded, the usual inspection should cover the matter of freedom from shrink or unsoundness of any character; trueness to pattern; good surface free from scale; normal fracture; good toughness and ductility; all of which can be ascertained by surface inspection and the breaking up of a certain number of castings from each anneal."



(Courtesy of E. Touceda)

Figure 78. Malleable Iron Castings

Two castings from the same pattern—one in which shrink is present and the other which through proper heading and gating eliminated the shrink.



(Courtesy of E. Touceda)

Figure 79. A Difficult Malleable Iron Casting

Section cut through a casting to show what the foundry is called upon to do in the way of disproportionate sections.

The Purification of Pig Iron

Wrought Iron and Carbon Steel.—Although cast iron and malleable irons are important and greatly used forms of iron, their physical properties do not come up to many service requirements of strength and ductility. These requirements necessitate the reduction of the amounts of certain elements in the pig iron to lower limits which have been prescribed by experience.

The most important of these elements are carbon, silicon, and, at times, phosphorus.

Oxidation is the essential chemical principle upon which the purification process is based, and there is considerable heat generated in the reactions which take place, as follows:

	Calories of Heat Generated	
Reactions	Per Kg. of Metal	Per Kg. of Oxygen
$Si + O_2 = SiO_2$......	6,428	5,625
$Mn + O = MnO$......	1,653	5,681
$C + O = CO$.......	2,430	1,823
$Fe + O = FeO$.......	1,173	4,106
$P_2 + O_5 = P_2O_5$......	5,703	4,562

If these reactions take place rapidly, there is no need of extra fuel, for the temperature may be maintained without. But if the reactions are slow, then extra fuel is needed to furnish the necessary heat.

Silicon and manganese oxides are both insoluble in molten iron and rise to the top as part of the slag. Further combination with basic constituents such as iron or calcium oxide renders the slag still more fluid. The CO bubbles off as a gas. A little of the FeO remains dissolved, but most of it goes into the slag.

Phosphorus will oxidize freely to the gas P_2O_5 but under the conditions prevailing in steel-making will not be eliminated until it is combined with lime to form stable calcium phosphate, $CaO_4P_2O_5$. To accomplish this end, lime additions to the bath are necessary and form the essential features of the basic process. The oxygen may be obtained from the air or by adding Fe_2O_3 to the bath in which case the iron becomes part of the resultant metal when the oxygen is liberated to combine with the phosphorus.

Wrought Iron.—(From Wrought Iron Research Association.)

"Wrought iron is the only commercial metal which is not obtained through the process of melting and casting, but is made by welding together separate small particles into a single large piece. Only by the process used in manufacturing wrought iron is it possible to incorporate the silicate slag which is found in wrought iron and is a large factor in the prevention of corrosion. Genuine wrought iron consists of pure iron as the base metal with a siliceous slag minutely and uniformly distributed throughout the mass.

"Puddling is a process for the production of wrought iron from pig iron by the action of the flame assisted by agitation, whereby most of the silicon, manganese, carbon, phosphorus, and sulphur is removed by oxidation.

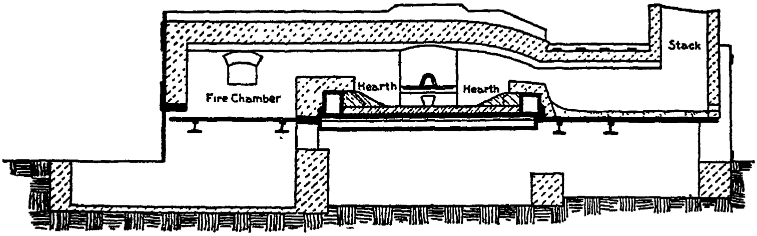
"The process consists of the following steps: (a) making bottom and fixing; (b) firing, the most important of all, and continuous throughout the entire process; (c) charging the pig iron; (d) melting; (e) adding roll-scale to the bath; (f) puddling; (g) balling; (h) drawing.

"(a) In a furnace the first step in puddling is the preparation of the bottom and fix. For this purpose, crop ends of wrought iron pipe are charged upon the hearth of the furnace and, by means of an oxidizing flame, a basic oxide of iron is produced. This infusible slag forms a hard, smooth surface; its function is to resist so far as possible the attack of the more siliceous puddling slag and retain a fairly smooth surface that will not invite "sticking" of the iron. The fix forming the sides of the hearth is composed of a refractory iron ore as low in silica as possible and is generally ground and applied in a plastic state.

"(b) Firing is continuous throughout the refining period. Particular skill is required in this, as on it depends the proper carrying out of the entire process.

"(c) The furnace is now ready to receive the charge of pig iron (usually 1,200 pounds in a double furnace), the composition of which is governed by the quality of the puddle bar desired. (See Figure 80.)

"(d) After the pig iron is charged, the puddler endeavors to fuse the whole charge as nearly at one time and at as low a temperature as possible. This is accomplished by moving the pigs about with a rabble (a square iron rod about 7 feet long), thereby exposing fresh surfaces to the flame and to the dissolving influences of the slag bath. The fusion of the pig iron and part of the puddle slag remaining after the working of the previous heat takes place simultaneously at a temperature of about 2,150 degrees Fahrenheit. The slag produced during the melting oxidizes and absorbs a large portion of the silicon and manganese. (See Figure 81.)

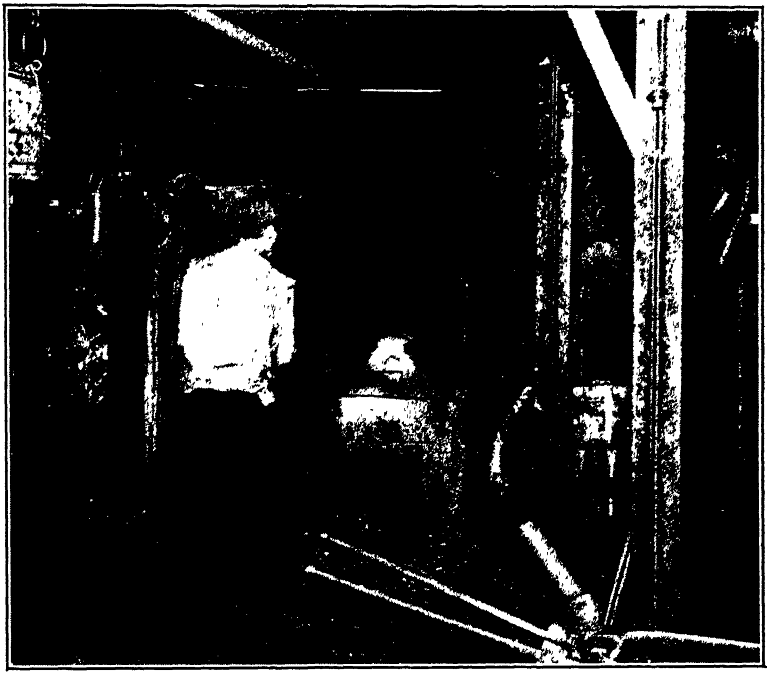


(*Courtesy of Reading Iron Co.*)

Figure 80. Longitudinal Section—Modern Double Puddling Furnace

"(e) Enough pure oxide of iron in the form of a scale is now added to chill the molten mass to such a degree that the bath of molten iron thickens, thereby making possible the thorough and uniform association of the individual particles of iron and oxide.

"(f) As the temperature increases and the bath of slag and iron again becomes fluid, rapid decarbonization takes place, giving off a large volume of carbon monoxide gas, which causes the bath to swell and to produce what is known as the 'high boil.' Vigorous agitation of the bath is vitally important throughout the process, to produce uniform conditions in all parts and prevent any portion continuing to rest upon the relatively cold bottom. During the high boil, individual grains of iron can be seen moving about freely in the surrounding slag. When the elimination of the carbon is nearly completed, the boiling subsides and the apparent volume of slag is reduced; this is known as the 'drop.' The grains of iron, each en-



(Courtesy of Wrought Iron Research Association)

Figure 81. Puddler Using a Bar to "Puddle" the Charge in the Furnace

veloped in slag, form clusters, from which the excess slag drains off and rests tranquilly on the bottom.

"(g) The iron at the bottom of the furnace is naturally cooler than that above. This necessitates turning over the spongy mass, and, while this is being done, it is parted into individual balls and then (h) 'drawn' (Figure 82) and taken to the squeezer as shown in Figure 83.

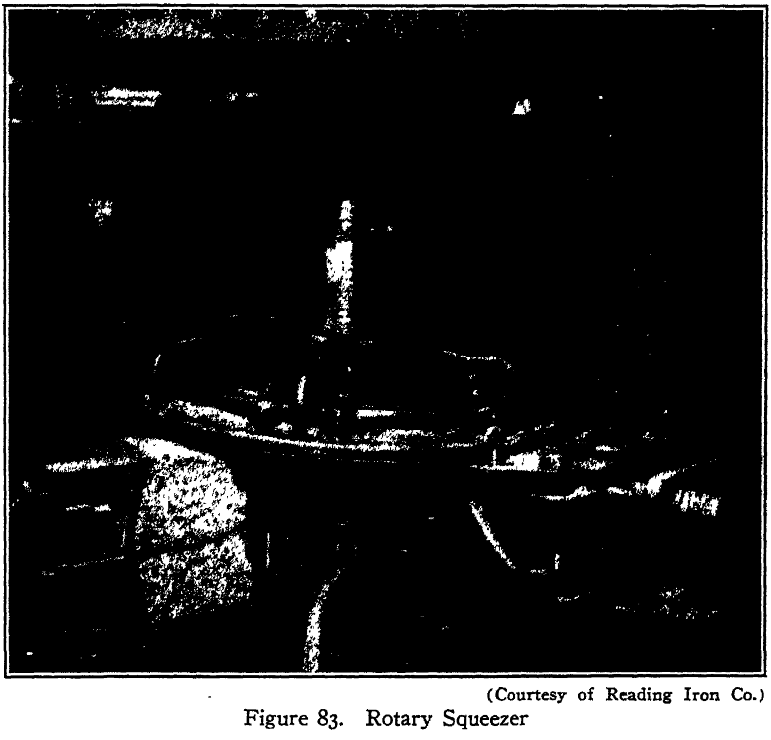
(Courtesy of Wrought Iron Research Association)

Figure 82. Removing the "Puddle" Ball from the Furnace

"The squeezer most commonly used is the rotary or coffee-mill type; this compresses the open sponge, and, since the slag is liquid at a lower temperature than the iron, forces out the excess slag and produces a roughly cylindrical mass or 'bloom.'

While still hot, the squeezed bloom is immediately passed to the bar mill where it is rolled into puddle bar, from which genuine wrought iron muck bar is made. (Figures 84 and 85.)

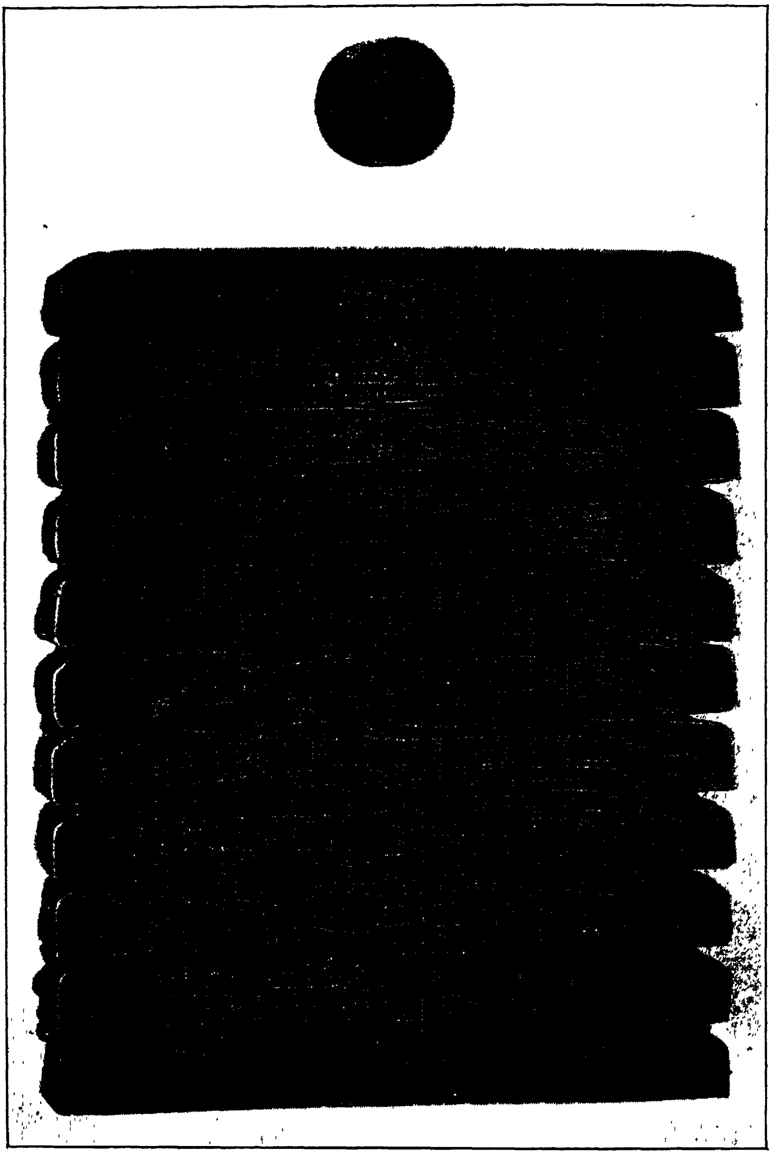
"Emphasis should be given to the importance of suitable slag. Proper slag is vital throughout all the stages. Its composition is controlled by additions, the temperature and character of the gases (these being regulated by the condition of the fire and the position of the damper), and by the absorption of some of the bottom and fix.



(Courtesy of Reading Iron Co.)

Figure 83. Rotary Squeezer

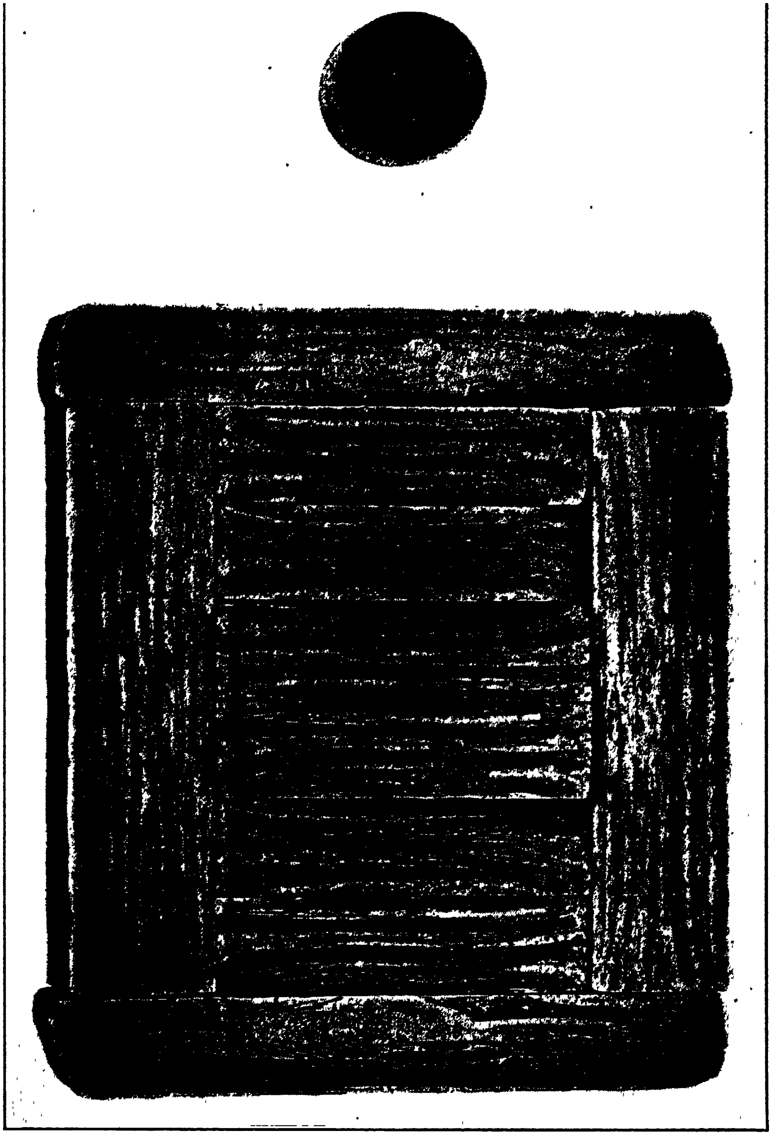
"By reason of decreased fusibility through the elimination of the elements silicon, manganese, sulphur, phosphorus and carbon in the pig iron, crystals or grains of iron form at a



(Courtesy of Wrought Iron Research Association)

Figure 84. Standard Slab Pile

Etched to show structure of muck bar prior to rolling. Small insert shows the etched structure of a 1 in. round rolled from this style of pile.

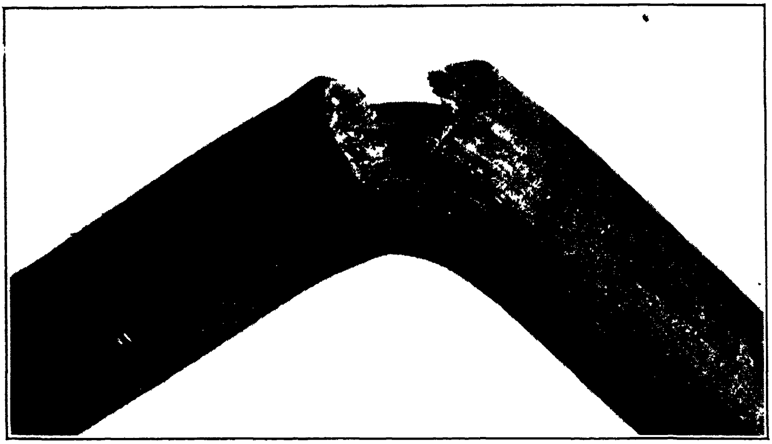


(Courtesy of Wrought Iron Research Association)

Figure 85. Standard Box Pile Sometimes Used for Rolling Staybolt Iron

Insert shows round rolled from above pile. Some makers of wrought iron use the box pile for re-working puddle bar, but neither method of piling has a decided superiority over the other; most wrought iron mills use the one best suited for their purpose.

relatively low temperature. These grains, existing as individual units, move about freely in the slag bath, which is maintained in an agitated condition by the high boil and the rabble of the puddler. Each grain, then, is surrounded by an envelope of slag, which, being of a siliceous nature, is practically incorrodible. This slag coating persists throughout all subsequent operations and is the direct cause of puddled iron's remarkable resistance to corrosion, to shock and to vibration. During rolling, the grains of iron and slag are elongated into fibres, which are alike visible under the microscope and to the unaided eye. When seen without magnification, the ruptured surface presents a beautiful rope-like structure, as indeed, it is. This siliceous slag covering to each fibre is the active resistant to corrosion; and the rope-like structure gives a freedom of movement under stress and prohibits continuity of fracture. Consequently, when rupture finally occurs, it is only after the individual fibres have let go gradually (Figure 86).



(Courtesy of Wrought Iron Research Association)

Figure 86. Nick-Bend Test for Wrought Iron

Appearance of a wrought iron fracture which is fibrous instead of crystalline. The fracture test is an easy method to tell the difference between wrought iron and steel. A wrought iron fracture shows a dull gray, fibrous structure, while a steel fracture will be brightly crystalline, due to the absence of slag fibres.

"Chemical analysis of genuine wrought iron:

C	Mn	Phos	Sul	Si
0.02 to 0.06	0.02 to 0.08	0.080 to 0.150	0.015 to 0.025	0.10 to 0.20

"It is essential that the carbon, manganese and sulphur be kept as low as possible. The phosphorus and silicon content depends on the slag content. The more highly refined the material, the lower the phosphorus and silicon."

Physical Properties of Wrought Iron.—On account of its plastic origin and the fact that it contains streaks of slag, the strength and ductility of wrought iron are somewhat lowered from that of the free iron as distinguished from the slag streaks. Wrought iron has better tensile properties where the stress is in the direction of rolling than when across it. In fact, the resistance to stress and strain in various directions depends upon the direction and distribution of the slag streaks. Wrought iron is extensively used for boiler tubes, pipes, and chains and for parts of electrical machinery. In cases of repeated stress wrought iron shows peculiar resistance to the propagation of cleavage plane and final fracture. Wrought iron shafting subject to torsional vibration and shock has stood for years where steel with much better static properties will fail. The purity of the iron and the interference of the slag has been regarded as responsible for the remarkable durability of wrought iron in exposed places.

The table below shows fair average values for the physical properties of wrought iron.

Tensile Strength lb. per sq. in.	Yield Point lb. per sq. in.	Elongation in 2 in.	Reduction of Area
48,000	30,000	30%	45%

Modulus of elasticity about 27,000,000 lbs. per sq. in.

"The physical properties of wrought iron change slightly as it becomes more highly refined. As a rule all the physical properties are improved by further refining of the material through piling and re-rolling."

The fracture of good wrought iron should appear fibrous or shreddy. If it looks coarsely crystalline, it is an indication of poor material.

Properties of Wrought Iron.—(From Wrought Iron Research Association.)

"Wrought iron has several special properties which are not possessed by any other ferrous metal. When the puddle ball is withdrawn from the puddling furnace the grains of almost pure iron are surrounded by liquid slag protecting them from oxidation. During the squeezing operation and each successive rolling operation a large part of this slag is expelled, and that which remains is elongated into filaments in the direction of rolling. These slag filaments, coupled with the extreme purity of the base metal, are the essential features of wrought iron which distinguishes it from other ferrous metals. (See Figures 87 and 88.)

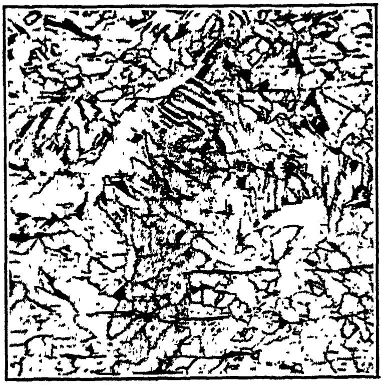
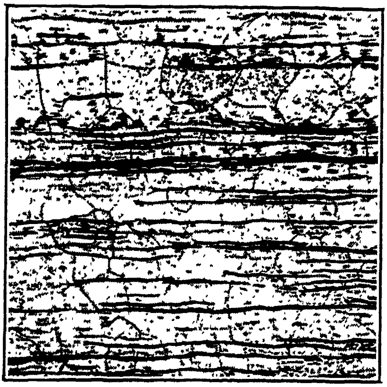


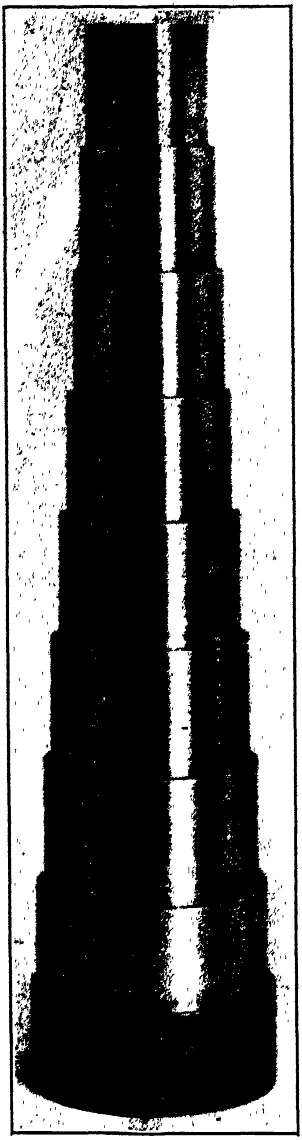
Figure 87. Poor Wrought Iron Showing Steely Structure with Little Slag



(Courtesy of Reading Iron Co.)

Figure 88. Good Wrought Iron, Practically Carbonless Iron with Pronounced Streaks of Slag

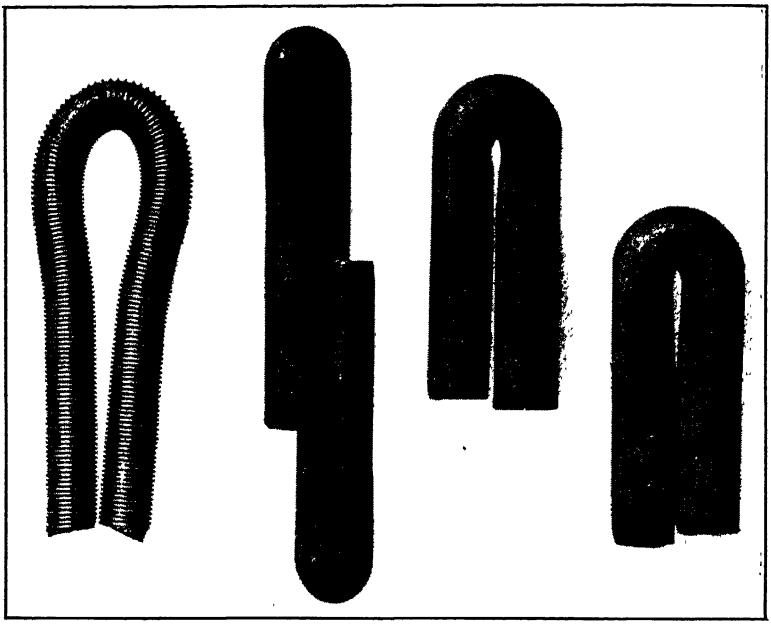
"The amount of slag in wrought iron is usually about 3% by weight. It varies, however, between 1% in highly refined wrought iron to 8% in muck bars. Due to the fact that the slag is about half as heavy as the metal, it varies between 2% to 16% by volume. The slag is a glasslike substance belonging to a group of compounds called silicates, which are non-corrodible. The distribution of the slag in the base metal is in minutely subdivided filaments, which due to forging and rolling are all parallel to each other, quite often recognizable with the naked eye after an acid etch, however, they can be seen more clearly by the aid of a microscope. In fact the microscope is essential to determine accurately how far the minute slag filaments are spaced apart from each other. The microscope has shown that good pieces of wrought iron which did not materially corrode during decades and even centuries of exposure, but were merely covered with a dense and coherent surface layer of rust, had the slag filaments spaced apart at least 0.0029 inch, quite often however as close as 0.00093 inch. The thickness of the slag filaments varies between 0.00012 to 0.0055 inch. Calculations from the average of the above figures have shown that in one square inch on the transverse plane there are over 50,000 slag filaments. These slag filaments act as



(Wrought Iron Research Association)

Figure 89. Step Test of Wrought Iron

'insulators' against the inroads of corrosion, as they are non-corrodible, and effectively halt progressive corrosion which is the cause of most steel failures. The oxide or rust which is formed on the surface of wrought iron is very tenacious, unlike the rust formed on steel which peels off of its own accord.


(A) (B) (C) (D)

(Courtesy of Wrought Iron Research Association)

Figure 90. Standard Bend Tests for Wrought Iron

(a) shows a piece of genuine wrought iron threaded and then bent cold. Note the clean, sharp threads. (b), (c), and (d) show standard bend tests used in testing wrought iron. (b) shows a piece of wrought iron bent cold in opposite directions. Note the absence of any flaw at bend. (c) shows a hot bend. (d) shows a piece of wrought iron heated to a cherry heat, quenched, and bent.

This tenacious coating of rust which forms on the surface of wrought iron has a tendency to protect the metal from further rusting.

"The slag itself melts at welding temperatures, acting as a flux. This fluxing of the slag cleans the surface and thereby a sound weld is secured.

"The slag filaments divide the iron into a series of crystal 'columns.' This fibrous structure gives to wrought iron a high degree of toughness and accounts largely for its ability to withstand the conditions set up by vibration and shock."

Figures 89 and 90 show the step tests and bend tests for wrought iron. All railroads require the step test. The purpose is to show that the material is clean and free from large slag inclusions so that clean, sharp threads may be obtained.

The Wrought Iron Research Association is authority for the following statements:

"The slightly rough surface of wrought iron causes a protective coating to adhere more closely than on the smoother surface of steel. Galvanizing will not peel off of wrought iron when the material is bent or hammered. This is a method used to determine whether a piece of galvanized pipe is wrought iron or steel where there are no identification marks on the pipe. If the end of a piece of galvanized wrought iron pipe is hammered down flat the galvanizing will not peel off, but the pipe will fracture at the smaller radius of the bend. If a piece of steel pipe is hammered down flat, the galvanizing will peel off and there will be no fracture at the radius of bend. This is a positive means for determining whether or not a piece of pipe is wrought iron or steel."

Steel

Carbon Steel.—Although there are some exceptions as will appear later, ordinary carbon steel differs from wrought iron in that it is of molten, instead of plastic, origin and thus practically free from slag.

It differs from cast iron in that it is malleable in at least some range of temperature.

Carbon steels are classified in various ways: the most important being according to carbon content and the method of manufacture.

Acid and Basic Steels.—The fundamental difference between acid and basic steels is the type of slag; in the former process, slags of acid character, that is, high in SiO_2 or with the silica unsatisfied, are formed, while the basic process provides basic slags, usually by lime additions, to more than satisfy the silica and to have basic constituents predominate. In order to insure these conditions it is necessary to line acid furnaces with acid material such as silica, ganister, or mica schist, etc., and basic furnaces with basic refractories, such as magnesite or dolomite. These linings prevent the scouring action which would otherwise take place.

The acid process will not eliminate phosphorus. The basic process will eliminate phosphorus and under the right conditions eliminate some sulphur.

Purer material must be used in the acid process and it has generally been supposed that acid steels were superior. They have been used for steel foundry work because they lie quieter in the mold. Lately it has been proved that, with proper care, basic steel may be produced of as high a grade as acid steels, and at a somewhat lower cost.

The classification according to carbon content is:

Low carbon steel..........	0.30% carbon
Medium steel.............	0.30 to 0.60% carbon
High carbon steel..........	Above 0.60% carbon

The percentages as given are purely arbitrary and are not even standard or agreed upon but the essential differences are as follows:

Low carbon steel is soft and ductile and is used for pressed and drawn work, and wherever a soft, strong, and tough material is desired. It cannot be appreciably hardened by heat treatment.

Medium carbon steel is increasingly stronger as the carbon content increases, so that its strength and toughness may be considerably increased by heat treatment. It hardens but little.

High carbon steel is stronger and more brittle. It responds well to heat treatment and readily hardens when quenched. It is otherwise known as carbon tool steel.

The classification according to method of manufacture is:

Bessemer steel
Open hearth steel
Electric steel
Crucible steel
Duplex steel

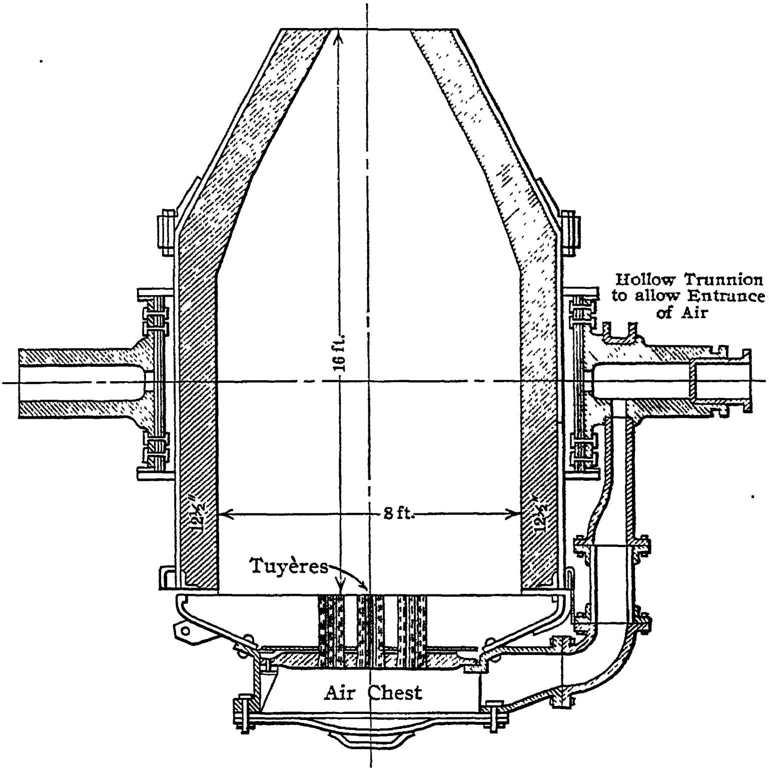

Hollow Trunnion to allow Entrance of Air
16 ft.
8 ft.
12½"
12½"
Tuyères
Air Chest

Figure 91. Section of Bessemer Converter

Bessemer Steel.—Bessemer steel gets its name from Sir Henry Bessemer who had a great deal to do with the development of the process of manufacture. It is made in a sort of pear shaped "converter" open at the top and with small openings (called tuyères) in the bottom through which air may be blown. (See Figures 91 and 92.) The operation of the process is as follows: The converter is tilted on its side and a charge of from 10 to 25 tons of molten pig iron is introduced through the "mouth." Air pressure is turned on, and the converter tilted into the upright position. Air is blown through the molten mass and the impurities, principally silicon and carbon, unite with the oxygen at such a rapid rate that the necessary temperature is maintained without extra fuel.

(Courtesy of American Steel & Wire Co.)

Figure 92. Bessemer Converter

The acid process is the only form of conversion used in the Bessemer process in the United States, because no domestic ores contain enough phosphorus to make the basic process practical.

Ores for the basic Bessemer process should contain in excess of 1% of phosphorus.

The process is difficult to control and the product depends entirely upon the skill of the operator. Also on account of the practice of blowing air through the mass, bubbles become entrapped and also iron oxide is formed and is more or less dissolved. This tends to produce a relatively unsound and dirty material which is one of the chief disadvantages of Bessemer steel. Additions of ferromanganese or spiegeleisen serve to cleanse the melt and also to recarburize to the desired extent.

The time of a "blow" is about 20 minutes and in this great speed of conversion together with the fuel economy lies the chief advantage of the Bessemer process.

When operated in conjunction with a steel plant where a continuous supply of molten iron from the blast furnaces is available, a tremendous tonnage may be produced at a cost lower than is possible with any other type of steel.

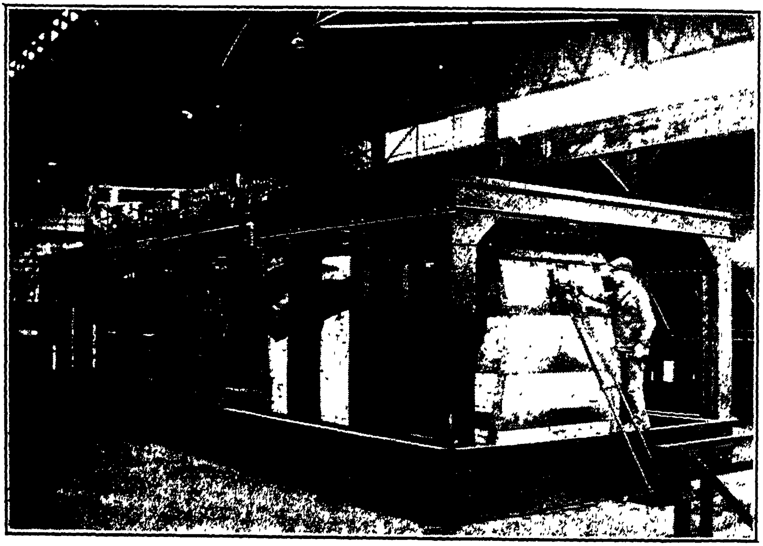
Formerly, Bessemer steel was used for structural shapes, rails, plates, etc., but since 1920 or thereabouts its use for these purposes has gradually been discontinued. Today its use is mainly confined to such products as tin plate, skelp for pipe, roofing sheets, and for wire and bar stock and other purposes not requiring high strength.

Open Hearth Steel.—Open hearth steel is made in a reverberatory furnace and the charge varies from 15 tons in small furnaces to 100 tons in the larger ones. The charge consists of either cold or melted pig iron and steel scrap together with the material necessary to form the slag. (See Figures 93, 94, and 95.) Between 75% and 85% of the steel made in the United States is made by this process. Most of it is produced in basic furnaces; only about 3% being acid steel.

Metallurgists generally agree that acid open hearth steel is superior to basic open hearth steel because it is cleaner and generally more sound. However, its use is restricted to pro-

(Courtesy of Wellman-Seaver-Morgan Co.)

Figure 93. Fifteen-Ton Tilting Open Hearth Steel Furnace—Pouring Side

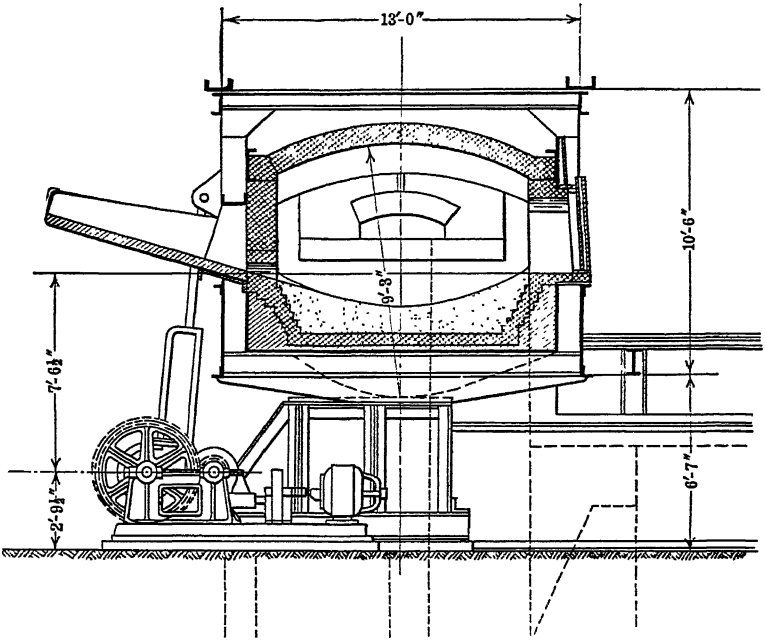


(Courtesy of Wellman-Seaver-Morgan Co.)

Figure 94. Fifteen-Ton Tilting Open Hearth Steel Furnace—Charging Side

duction of high-grade alloy steels and tool steels; steels for heavy ordnance, guns, etc., and difficult places where the requirements are very rigid.

The reason for the prevalence of the basic open hearth process is on account of the scarcity of guaranteed low phosphorus scrap and the higher price of low phosphorus pig iron.



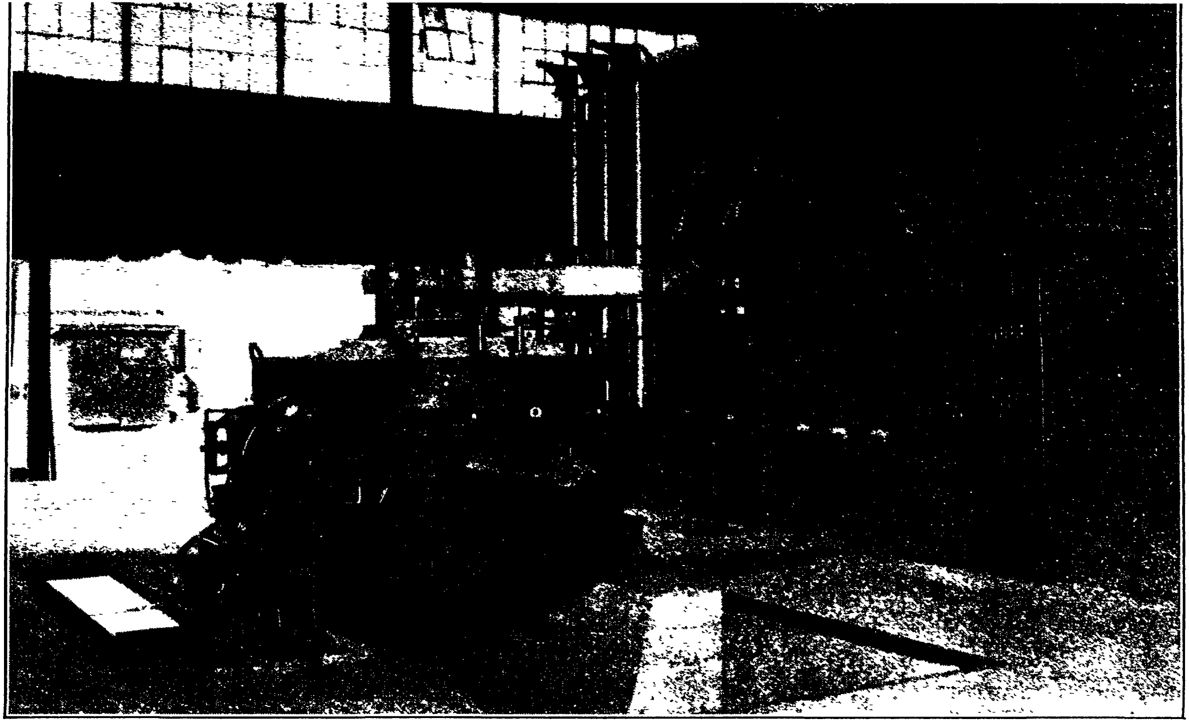
(Courtesy of Wellman-Seaver-Morgan Co.)

Figure 95. Cross-Section of Tilting Open Hearth Furnace

Since phosphorus is practically entirely eliminated in the basic process, and 10% to 40% of the sulphur as well, the basic process has boomed and the acid process gone into discard for high production of steel for ordinary purposes.

Basic open hearth steel is used for rails, structural shapes, plates, sheets, rods, wire, etc.

The open hearth process is slow compared to the Bessemer.



(Courtesy of Pittsburgh Electric Furnace Corp.)

Figure 96. Electric Steel Furnace

It requires 6 to 8 hours for conversion and therefore requires extra fuel to maintain the necessary temperature. Gas or oil is generally used for fuel and the air is preheated by the regenerative principle. It may be accurately controlled and the product is uniform.

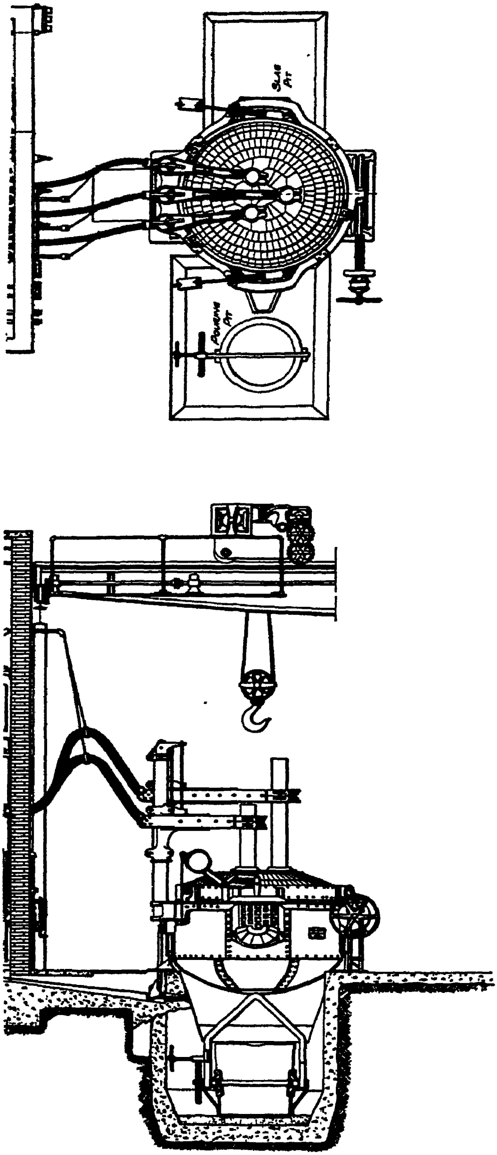
Duplex Steel.—In order to take advantage of the rapidity of the Bessemer process and cut down the time of the open hearth process, a combination of the two has been used to some extent. One other reason for this combination is the difficulty of obtaining proper steel scrap, which is rather necessary for the open hearth. In the duplex process a part of the reduction is carried out in the converter and then the material is removed and finished in the open hearth.

Electric Steel.—Electric steel, as its name implies, is the product of the electric furnace. (See Figures 96 and 97.) During the last 15 or 20 years this process has made rapid strides in the United States.

The acid electric process is practically identical with the acid open hearth process except that the heat is furnished by electricity. Its chief use is in the foundry where smaller charges may be more economically handled by this process than by the open hearth process.

The basic electric process is important because of the possibilities of slag and atmosphere control. Since it is possible to make the atmosphere either reducing or oxidizing, the process is divided into two parts: first, the oxidizing period in which the slag and process are practically identical with the basic open hearth process. In this part of the process oxygen is introduced as iron oxide in the ore, and oxidizes the silicon, manganese, phosphorus and carbon in the same way as in the basic open hearth.

After oxidation is complete the slag is drawn off, and a new slag made. The new slag consists of lime, coke, and fluorspar, and is *very different* from any other slag used in steel-making.


Slag Pit
Pouring Pit

(Courtesy of Pittsburgh Electric Furnace Corp.)

Figure 97. Arrangement of Electric Steel Furnace

At the high temperature of the electric furnace, the carbon reacts with the lime to form calcium carbide, a powerful reducing agent. The atmosphere is changed to a reducing condition and the carbide slag serves to deoxidize the metal bath completely. Thus the material is freed from ferrous oxide and other impurities, which are responsible for low quality steel. the carbide slag also has the power of reacting with the sulphur to form calcium sulphide which is soluble in the slag and thus removable. It is quite evident that by this process, using the two slags, it is possible to produce high-grade steel surpassed only by the highest grade crucible steels.

When hot metal is available the first part of the process is often carried out in the open hearth and the second or deoxidizing part in the electric furnace.

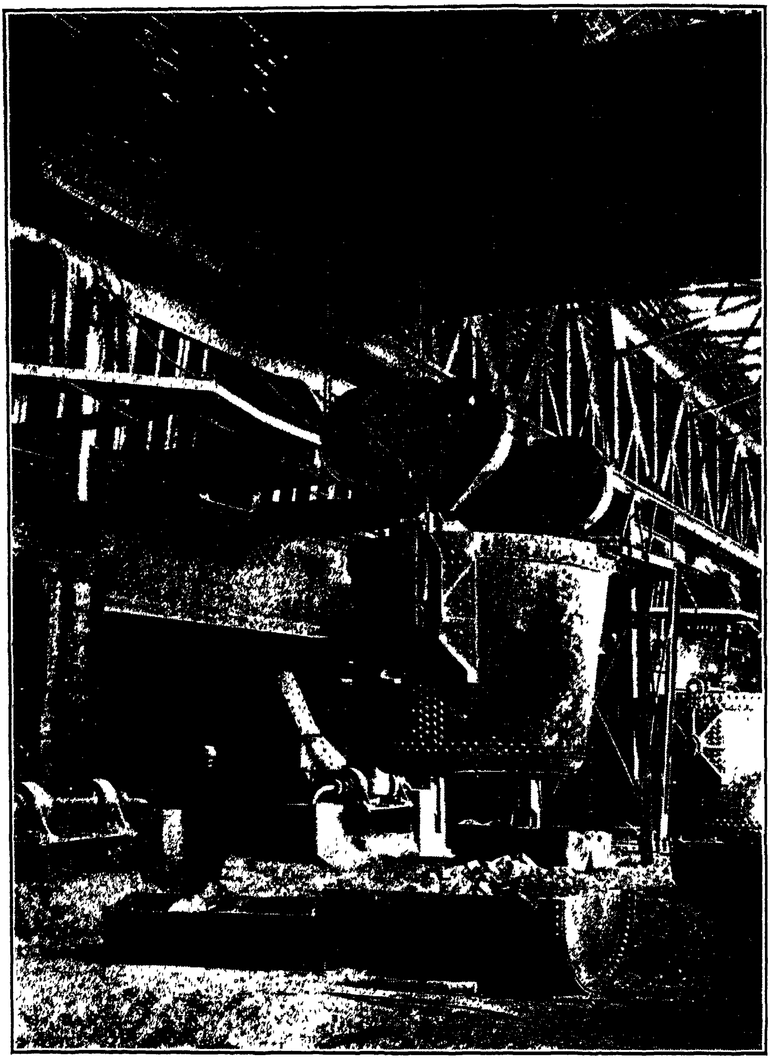
Crucible Steel.—Although it is claimed that just as good steel is possible in the electric process as by the crucible process, many still feel that the highest grade material is produced only in the crucible process.

The crucible process is not a refining process in any real sense. It is a remelting and alloying process, pure and simple, and only the highest grade raw material may be used.

It consists of melting wrought iron covered with charcoal in a graphite crucible, the charge being about 100 lb. per crucible. In America, steel scrap is sometimes used and ferrosilicon added just before the crucible is drawn.

Tool steels and various grades of alloy steels are made by the crucible process, but it is expensive and its use is limited to the production of articles of small weight or to special parts where a high-grade product must be had regardless of cost.

Production of Steel Merchant Shapes.—Although steel is sometimes cast into final form as steel castings, by far the greater part is reduced by mechanical work to the desired shape. Not only is this a convenient way to produce many of these "shapes" but the physical properties of the steel are much im-

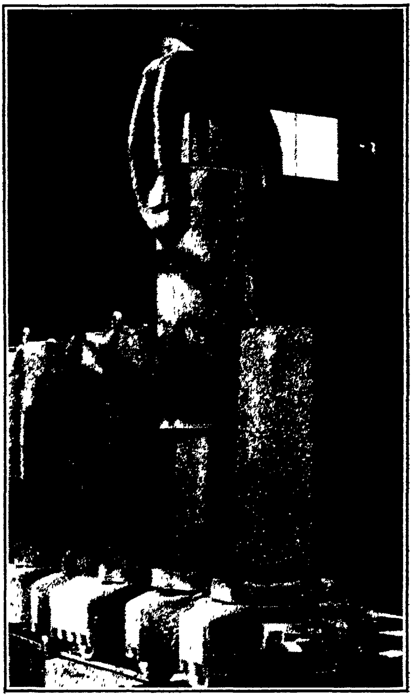


(Courtesy of American Steel & Wire Co.)

Figure 98. Fifty-Ton "Teeming" Ladle Ready to Receive the Charge from a Tilting Open Hearth Steel Furnace

proved. The three methods of producing shapes are hammering, pressing, and rolling.

The Ingot.—When steel is first tapped from the furnace it is caught in a large bucket or ladle (see Figure 98), which holds the whole charge. The ladle has a valve in the bottom so that the metal can be drawn off without disturbing the slag which floats on top. Clean metal is thus allowed to run into the ingot mold.



(Courtesy of American Steel & Wire Co.)
Figure 99. "Stripper" Removing Ingot Mold from Hot Ingots

Ingot molds vary in size, but in rolling mill practice they are usually rectangular or square in cross-section—12 in. by 12 in., to 20 in. by 20 in., and from 5 ft. to 8 ft. long. They taper slightly, the small end at the top, so that they may be withdrawn easily when the metal has cooled sufficiently. (See Figure 99.) The casting of the ingot is an important process, for defects in the ingot persist in the finished product. (See Figure 100.)

The most common defects in ingots are pipes, blow holes, segregation, slag, and the coarsely crystalline structure called ingotism. These defects are present in all ingots to some extent.

Pipes are formed by rapid cooling of the outside of the ingot and by the subsequent shrinkage and settling of the material.

Segregation of impurities occurs in the last portions to freeze, that is, around the pipe.

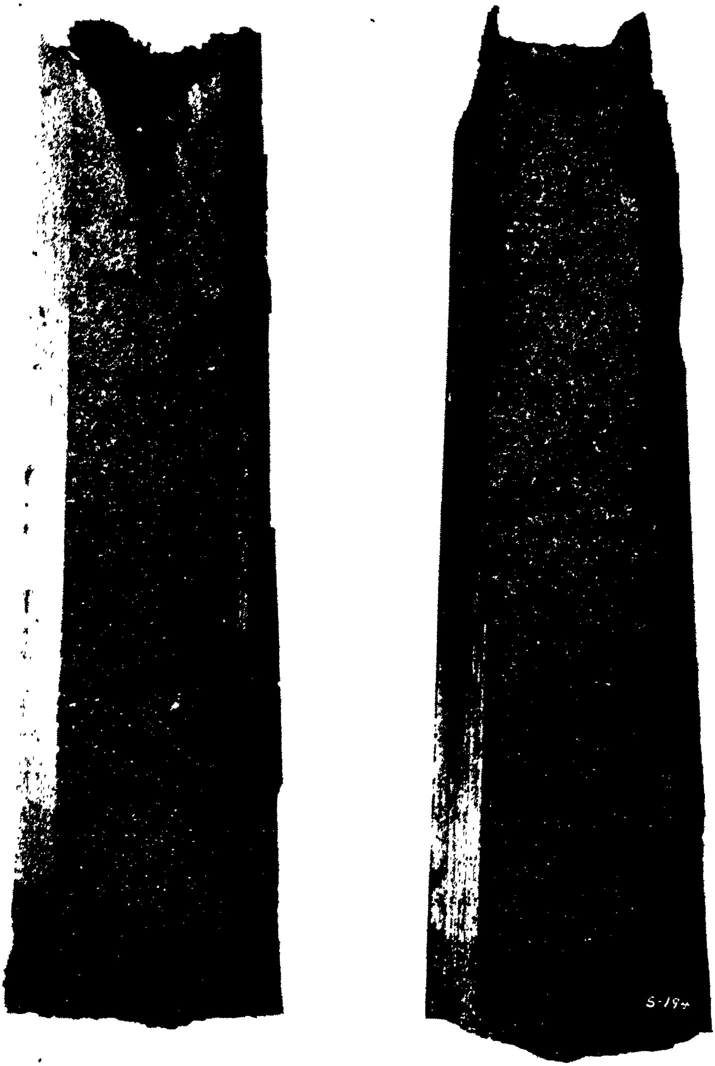
If the ingots are not properly "cropped," that is, if the piped and segregated ends are not cut off, then the defect will appear in the finished material.

Blow holes are formed by entrapped gases and by solidification of certain impurities which shrink more than the surrounding iron.

Ingotism results from very slow cooling from very high temperature. It is a coarse, open form of crystalline structure.

Preparation of Ingots for Rolling or Forging.—In order to prevent squirting out of the liquid interior, it is necessary to "soak" ingots in heat until they become of an even heat all through and perfectly solidified. This is accomplished in "soaking pits" fired just enough to retain the desired temperature.

Hot Rolling and Forging.—The processes of rolling and forging are a sort of kneading. The natural crystal formation is broken down; the structure is made more dense and much more homogeneous. The physical properties are much improved

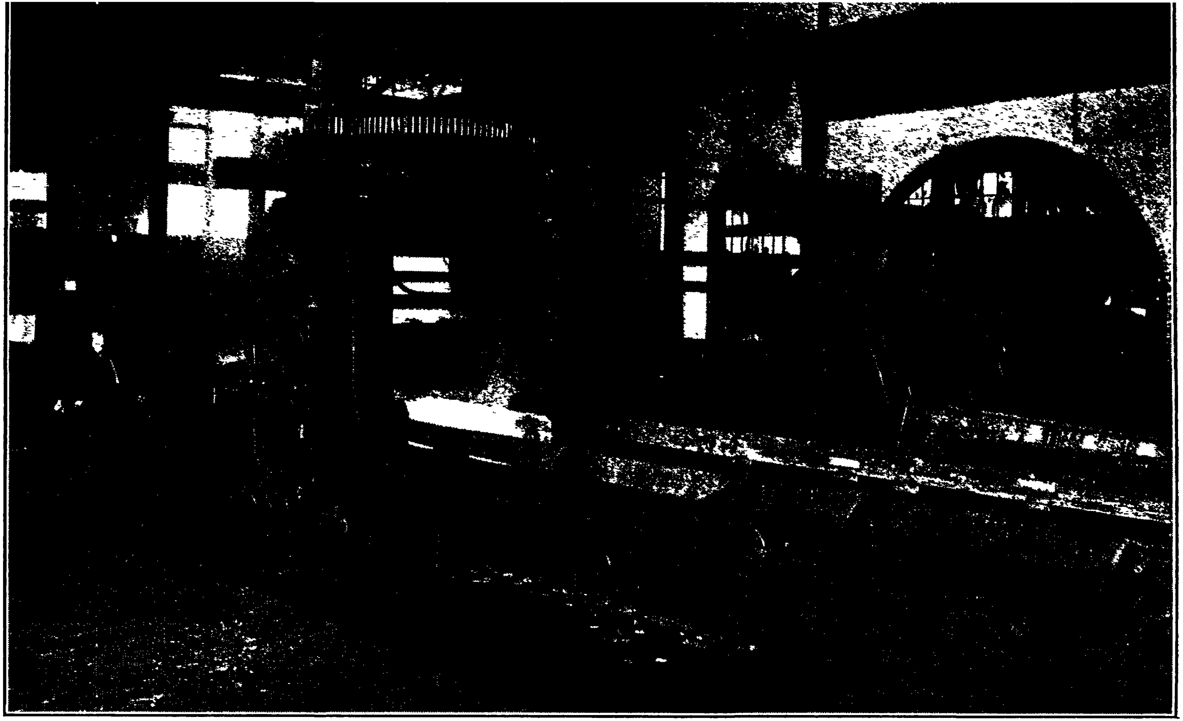


(Courtesy of American Steel & Wire Co.)

Ingot split to show deep "pipe" and tendency to segregation, necessitating heavy "cropping."

Ingot split to show absence of "piping" thus requiring a minimum of "cropping."

Figure 100. Steel Ingots Split to Show Defects



(Courtesy of American Steel & Wire Co.)

Figure 101. Two-High Reversing Blooming Mill at South Works, Worcester, Mass.

and there are no residual internal stresses if the temperature is maintained high enough. It is the practice, however, in production of some shapes to allow the temperature to drop a little just before the finishing operation. This slightly distorts some of the crystalline structure, sets up internal stresses, and slightly hardens the material.

Rolling is uniform and very rapid, but is restricted to certain standard shapes, viz., I-beams, channels, angles, etc., while forging may be used for much more intricate shapes but is much slower on a tonnage basis. The action of the forging press is much deeper than that of the steam hammer, or the rolling mill, and is consequently the best for very heavy material. Standard shapes, plates, sheets, pipes, and rods for wire are produced by rolling. (See Figure 101.)

Intricate forgings and small parts that cannot be rolled are generally made under the drop or steam hammer, while heavy forgings such as armor plate and cannon tubes are made under the forging press.

Pure Iron.—Chemically pure iron is not a commercial product. By careful laboratory processes it has been obtained very nearly pure. Swedish iron has been produced commercially as high as 99.8% pure iron, and a very low carbon steel, known as American Ingot Iron, has had a claimed purity of 99.94%. Electrolytic iron has been obtained in relatively large quantities at a degree of purity exceeding 99.9%.

Pure iron, in cooling from the liquid stage, forms a crystalline solid and the crystals in forming arrange themselves in aggregates, called grains. These grains start in various places called nuclei, but the start is at the coolest portions and proceeds toward the hottest regions.

When a sample of nearly pure iron is suitably prepared and examined under the microscope certain areas practically free from impurities and practically carbonless can be found, exhibiting therefore the structure of the pure metal.

Ferrite.—Ferrite is the mineralogical name given to pure, or rather, carbonless iron considered as a microscopical constituent. The ferrite of commercial irons and steels is not really pure iron, but iron holding small amounts of silicon, phosphorus or other impurities in solution.

Allotropy.—Several allotropic forms of iron are recognized and their existence complicates the study of the crystallization of iron.

At least three of these allotropic forms—called alpha, beta, and gamma iron—have been recognized, although there has been some discussion about the beta form. These forms are dependent upon the temperature. *Gamma iron* is the equilibrium form about 900° C. or 1,650° F.; *alpha* is stable below 760° C. or 1,400° F.; the *beta* stage is stable between 760° and 900° C.

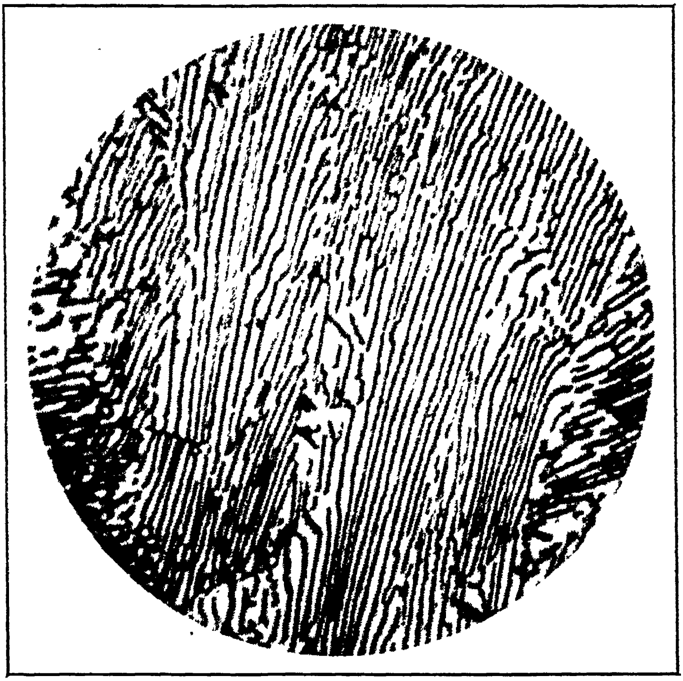
Physical Evidences of Change from One Form to Another.—The most noticeable physical evidences of change from the alpha to the gamma form on heating are: first, the sudden loss of magnetic properties; second, the contraction while the change is taking place. On cooling, there is a return of magnetic properties and an expansion while the change is taking place.

The temperatures at which these changes take place are called critical temperatures.

The Iron Carbon System.—The Physical Constitution bears a close relationship to the percentage of carbon present with the iron, and the temperatures at which the various allotropic changes occur become very much modified.

Before turning to the diagram to study these relations it will be necessary to discuss certain chemical and solubility relations between iron and carbon.

Liquid iron holds carbon in solution up to 6.67% if above about 1,500° C. Upon cooling much below 1,500° C. part of the carbon forms a chemical compound, solid iron carbide,



(Photograph by Francis F. Lucas)

Figure 102. Eutectoid Steel
Original magnification 2,800 times

Fe_3C, called *cementite*. Until the whole mass is solid, this carbide may be suspended in the liquid in the very high ranges of carbon content, or dissolved in solid "gamma" iron in the lower ranges.

Solid gamma iron with Fe_3C dissolved is called *austenite*. The limit of solubility of Fe_3C in gamma iron is at 2% of carbon or about 30% cementite. The maximum is at 1,130° C. and decreases as the temperature drops.

This limit of 2% carbon marks the boundary between steels and cast irons.

Alpha iron will not hold the carbide Fe_3C in solution. When the lowest temperature at which austenite can exist is reached on slow cooling, separation of the ferrite (α iron) and cementite *must* take place. The structure found at the lowest possible temperature (eutectoid) slowly cooled is known as pearlite. Under the microscope, slowly cooled material would appear as shown in Figure 102.

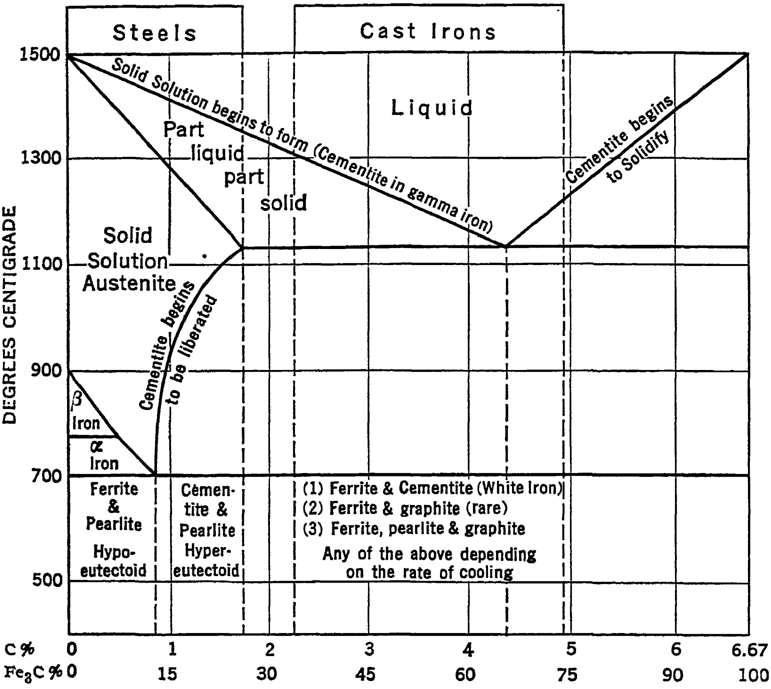


Figure 103. Equilibrium Diagram of Iron-Carbon System (Modified from Sauveur's Diagram)

The diagram (Figure 103) represents the constitution that will exist for irons with various carbon contents at any temperature from that of the melt to that of the atmosphere.

Heat Treatment of Steel.—It is well to note at this point that the equilibrium diagram, as shown in Figure 103, shows where structural modification of the grain formation takes place naturally upon very slow cooling. If the material is reheated, the reverse changes take place, but at slightly elevated temperatures. In carbon steel this difference may be as little as 10° C. or as much as 50° C. or 90° F.

Reflection on the above statement naturally leads to the query as to what will happen if the rate of cooling is more rapid

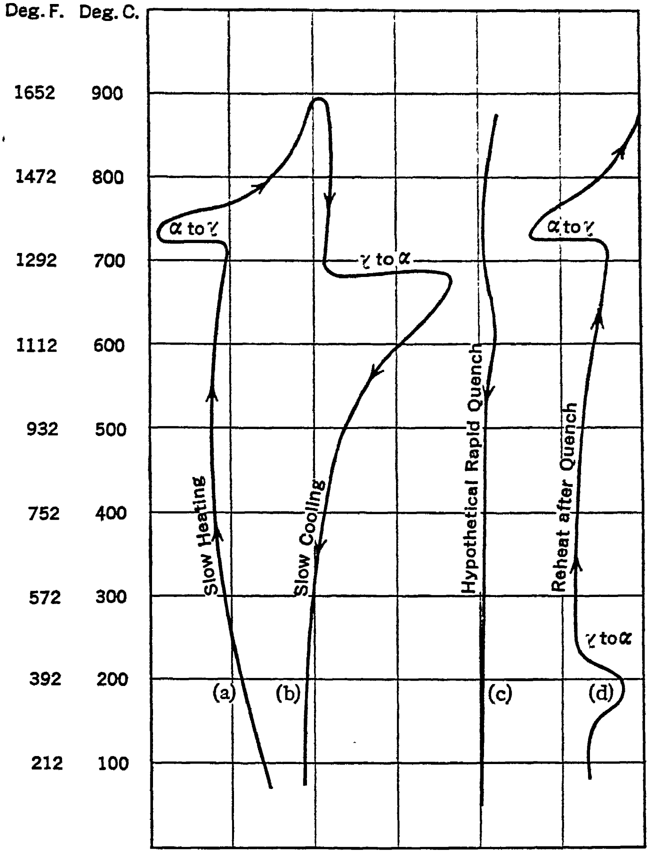


Figure 104. Type Curves of High Carbon Steel—Location of Transformation Point Under Various Conditions

and the answer is, in general, that the more rapid the cooling, the more the natural changes are suppressed until at extremely rapid rates they practically disappear. Ordinary carbon steel is extremely unstable under such very rapid cooling and if the temperature is elevated comparatively little, the changes which would naturally have taken place at the critical range begin to take place at the lower temperature.

These characteristics form the basis for heat treatment such as annealing, hardening, and tempering or drawing.

Change in Transformation Point.—The four curves of Figure 104 represent the temperature difference, as the temperature rises, between a steel sample which has a critical temperature and a sample holder which does not. Curves a and b indicate the relations on slow heating and slow cooling and show that the transformation from alpha to gamma iron on heating takes place at a somewhat higher temperature than for the reversal of the change, that is, from the gamma to alpha.

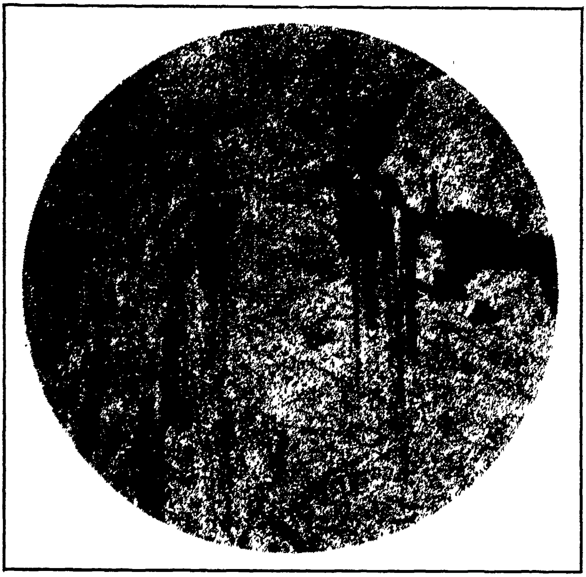
Curve c represents what may be expected in quick cooling, namely, that the gamma form of iron is maintained down to atmospheric temperature, because of the practically total suppression of the natural changes, the steel becoming rigid so rapidly that they cannot take place. Of course, the slower the cooling the less perfect this suppression.

Curve d represents what takes place on reheating a rapidly cooled sample. Starting at atmospheric temperature with the gamma phase, reversion to the alpha phase takes place at a comparatively low temperature, the change progressing as the temperature rises. On further heating the normal change from alpha to gamma will again take place exactly the same as in the case represented by curve a.

Between austenite or the gamma form of iron with more or less carbide, Fe_3C, dissolved in equilibrium above the critical range, and the ferrite form with no carbide dissolved, the equilibrium at the lower ranges of temperature, various transition stages occur.

It is the occurrence of these transition stages that produces the variation of physical characteristics of heat-treated steels. The methods of causing such occurrences and accurately controlling them are the methods of heat treatment.

Austenite.—Owing to its extreme instability, austenite in carbon steel can only be obtained in very small sections under the most drastic conditions of cooling from high temperature.



(Photograph by Francis F. Lucas)

Figure 105. Structure of Austenite (Solid Solution)

Obtained in carbon steel only by the most drastic quenching. Obtained in certain alloy steels by less drastic quenching.

Original magnification 3,230 times

Nevertheless, when such a stage is obtained, the grain structure is as shown in Figure 105.

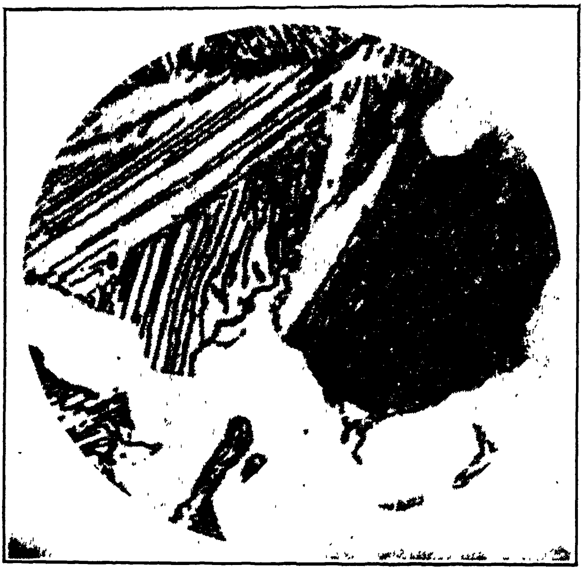
This stage is rather strong and peculiarly ductile. Showing rather different characteristics than the ductility in ferrite steels.

Pearlite.—The stable form for carbon steels at atmospheric temperature is the pearlitic stage. (See Figure 106.)

Figures 107 to 110 show some of the variations of constituents that may occur in this stage.

Figure 107 is almost pure ferrite, i.e., almost carbonless steel. The grain boundaries are those which existed when the steel was in the solid solution, or austenitic stage.

Figure 108 shows the structure of a low carbon steel (hypo-eutectoid) in which there is an excess of ferrite which appears as the white areas, while the black appearing areas are the pearlite which consists of alternate bands of ferrite (carbonless iron) and cementite (Fe_3C, a chemical combination). Under high power magnification the pearlite appears as in Figure 106.



(Photograph by Francis F. Lucas)

Figure 106. Structure of Pearlite (Annealed Carbon Steel)
Original magnification 3,230 times

Figure 109 shows the structure of annealed steel in which there is neither an excess of ferrite or of cementite. The car-

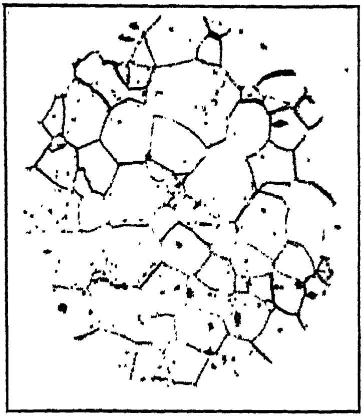
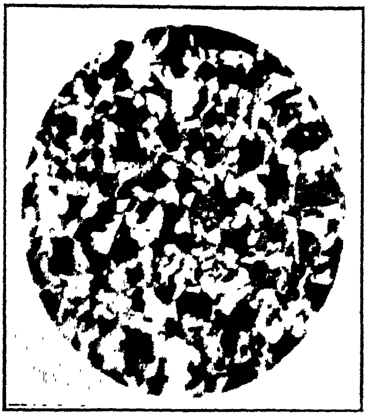


Figure 107. Structure of Ferrite. Very low carbon steel, practically pure ferrite



(Courtesy of American Steel & Wire Co.)

Figure 108. Medium Carbon Steel (30%-40%) Carbon, Ferrite (white) and Pearlite (black)

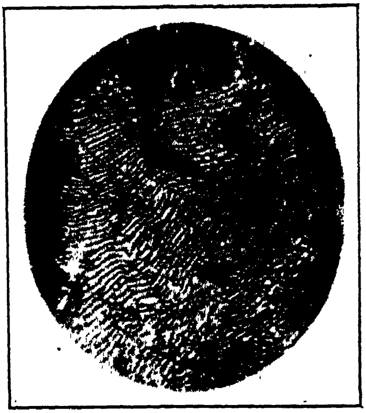
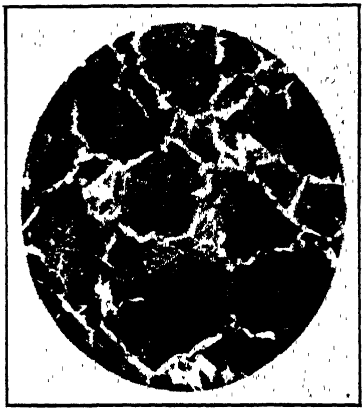


Figure 109. Eutectoid Steel .85% Carbon, Alternate Bands of Ferrite and Cementite (Pure Pearlite)



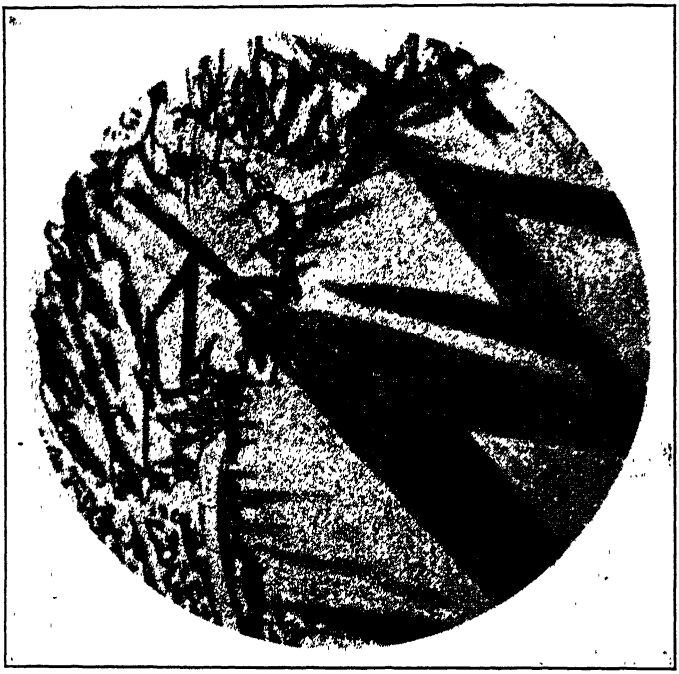
(Courtesy of American Steel & Wire Co.)

Figure 110. High Carbon Steel (1.30%-1.40%) Carbon, Pearlite (dark), Cementite (white)

bon content is about 0.85%. This is called *eutectoid steel* and the structure of the annealed sample is entirely pearlite.

Figure 110 shows the structure of a high carbon steel in which there is an excess of the carbide which appears as the white areas surrounding the areas of pearlite.

The pearlitic stage is the common annealed stage of steel in which there is the greatest possible combination of softness and ductility with whatever the carbon content happens to be. The ferrite constituent is soft and ductile, but the carbide is very hard and strong, but rather brittle.

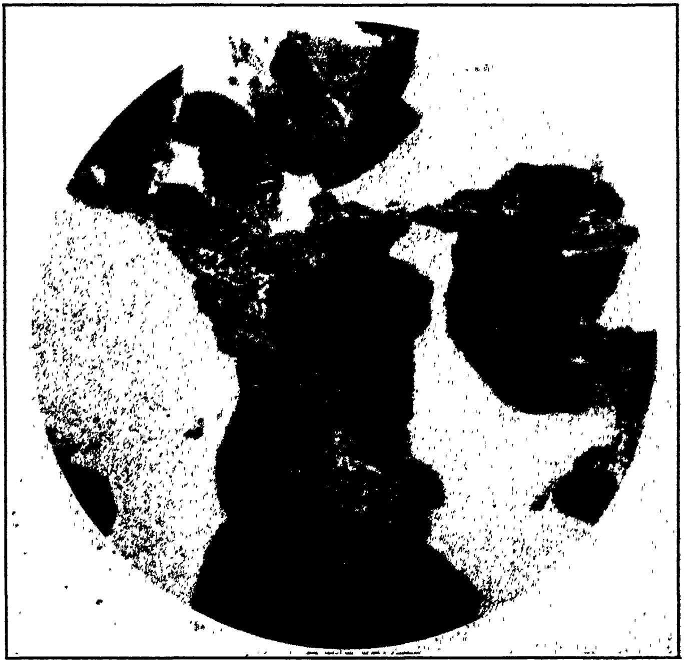


(Photograph by Francis F. Lucas)

Figure 111. Structure of Martensite Characteristic of Hardened Steel
Original magnification 3,230 times

Between the austenitic and the pearlitic stages there are the various stages of more or less tempered steels. Not only does the atomic arrangement of the iron undergo a change between these two stages, but the carbide of iron which was in solution in the austenitic stage must go out of solution in the pearlitic stage.

Although the steel is comparatively soft in the two extreme stages, it becomes very hard and brittle in the intermediate stages nearest the austenite end. The hardness decreases gradually as the transition advances toward the pearlitic stage. The structure of the hard stage is customarily known as *martensite* (see Figure 111). As the temper begins to be drawn, a new structure begins to appear, intermingled with the martensite.



(Photograph by Francis F. Lucas)

Figure 112. Structure of Troostite Characteristic of Tempered Steel. Very Rarely Found Alone. Generally Accompanied by Martensite or Finely Divided Pearlite (Sorbite)

Original magnification 3,230 times

This characteristic structure of tempered steels is ordinarily known as *troostite* (see Figure 112). It is found mingled with martensite or austenite or both.

As tempering proceeds, the troostite passes into a finely divided, fairly uniform mixture of ferrite and cementite generally called *sorbite*. This sorbite is essentially the same as pearlite in that it represents separation between the ferrite and the cementite. It is different in that the particles of ferrite and cementite have not arranged themselves in the kind of pattern which is characteristic of fully annealed steel. The structure of the fully annealed stage is laminated pearlite as shown in Figure 106.

The capacity to gain strength on quenching, possessed by carbon steels, varies closely with the percentage of pearlite present in the annealed sample. Thus a carbonless steel, which has no pearlite, gains practically nothing, whereas an 0.85% carbon steel, which would be 100% pearlite, would gain approximately 100% strength.

Of course, besides this the higher carbon steels have a higher initial strength in the annealed state.

Effect of Grain Size upon Physical Properties.—Steel, in cooling slowly from the melt, crystallizes in polyhedral grains of very great size. Such large grains are rather brittle and various methods are used to reduce them in size.

Mechanical work, such as rolling or forging, is effective if continued until the material passes below the critical range, but heat treatment has a peculiar effect on the grain size and must be carefully controlled for the best results.

Suppose that the grain size at some elevated temperature was represented by the distance between two lines (Figure 113). On cooling to the atmospheric temperature, the size of these grains would remain unchanged. The passage through the critical range, on cooling, has no effect whatever on the grain size. But on heating, a different phenomenon is observed.

On the passage through the critical range the old existing grains are obliterated and fine, new grains form, so that just above the critical range the maximum refinement of the grains takes place and steels quenched from this temperature can be made to acquire their maximum toughness. On heating further above the critical temperatures, and in proportion to the time during which they are held at the high temperatures, an increase in grain size is noticed. Thus overheated steels become coarse-grained and brittle.

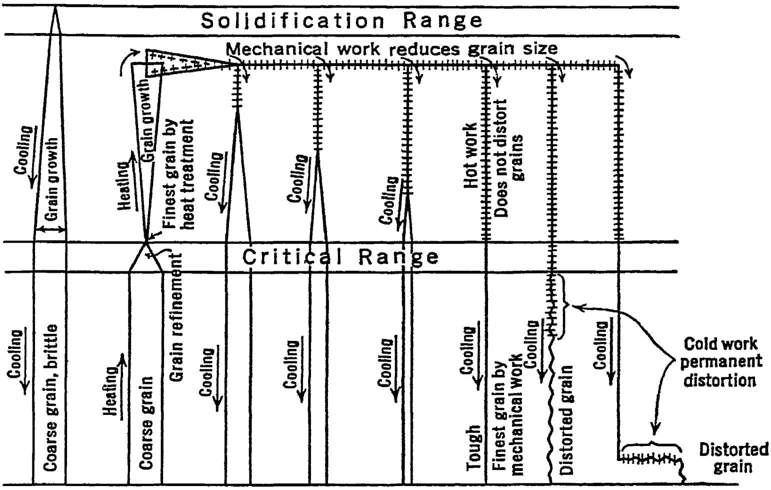

Solidification Range
Mechanical work reduces grain size
Cooling
Grain growth
Heating
Grain growth
Finest grain by heat treatment
Cooling
Cooling
Cooling
Hot work
Does not distort grains
Critical Range
Cooling
Coarse grain, brittle
Heating
Coarse grain
Grain refinement
Cooling
Cooling
Cooling
Cooling
Tough
Finest grain by mechanical work
Cooling
Distorted grain
Cooling
Cold work permanent distortion
Distorted grain

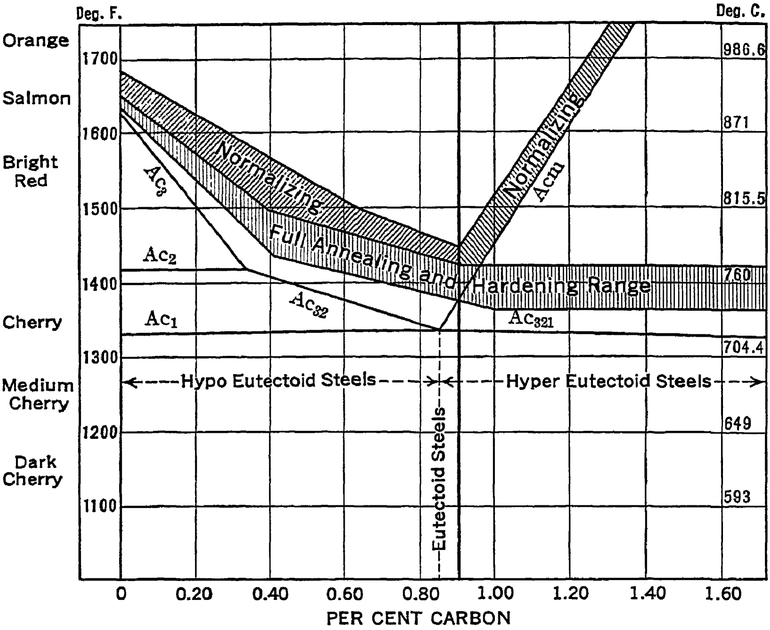
Figure 113. Effect of Heat and Mechanical Work on Grain Refinement (Modified from Sauveur's Diagram)

Heating for Annealing, Hardening, and Normalizing.—Figure 114 is the part of the iron carbon diagram which covers the range of steel. It is, however, constructed on the basis of the Ac points, or critical points on heating, rather than on a basis of the Ar points, on cooling.

Theoretically, it should be possible to accomplish full annealing or hardening and maximum refinement of the grain by heating just above the Ac_3 line, as shown in the diagram.

Practical considerations, however, demand a somewhat higher range for commercial practice. The range recommended by the A. S. S. T. is clearly indicated.

In order to dissolve completely the free ferrite of hypo-eutectoid, or low carbon steels, and the free cementite of the hyper-eutectoid, or high carbon steels, a higher range of temperature is necessary. In order to get uniform treatment it is often necessary to resort to this practice, followed by air cooling and subsequent reheating for annealing or hardening.



(Courtesy of Amer. Soc. for Steel Treating Handbook)

Figure 114. Critical Range Diagram for Iron-Carbon Alloys Showing Normalizing, Annealing, and Hardening Ranges

Various commercial steels require different times of soaking at the treating temperature and indicating and recording pyrometers are customarily used. Recently a new apparatus called the dilatometer has been put on the market. The dilatometer does not record the temperature but merely the expansion and contraction of the metal to be treated. Steel expands up to the critical range and then contracts while the transformation is taking place. When it again begins to expand the treatment is complete and maximum refinement is present. Very good results for treating for hardening are claimed for this method. It is, of course, not suited for drawing or tempering.

For drawing or tempering, either a pyrometer or the color of the oxide scale is used as an indicator of the proper temperature.

Quenching Mediums.—The rate of cooling is sometimes important and various mediums may be used. Hot lead, oils of various kinds, water, and brine are some of the most common quenching mediums.

In heat treating low carbon steels, the toughest steels result by heating to about 50° C. or 90° F. below the upper critical temperature, Ac_3, after quenching from above the critical range, but the treatment varies with the chemical analysis.

Effects of Mechanical Work.—Mechanical work is generally classified as cold work if the temperature is well below the critical range. It results, in general, in the distortion of the existing grain, but this distortion produces quite different effects according to whether the temperature is above the critical range or not.

Effect of Hot Work on Structure.—Austenitic structure tends toward symmetrical, equiaxed grains which grow as the temperature is raised. Hot work tends to distort and flatten these grains. The tendency for the austenite to remain symmetrical in form causes these elongated grains to break up into smaller grains which would grow again if not worked any more and if at a high enough temperature. The effect of hot work, then, is to knead the material, making it more homogeneous and tending to produce a fine-grained structure. From the standpoint of the doctrine of grain size, that strength and ductility are the accompaniment of fineness of structure, it is obvious that hot work is important as a means of improving the physical quality of the material. Good practice requires that the material shall be nearly down to, or even a little

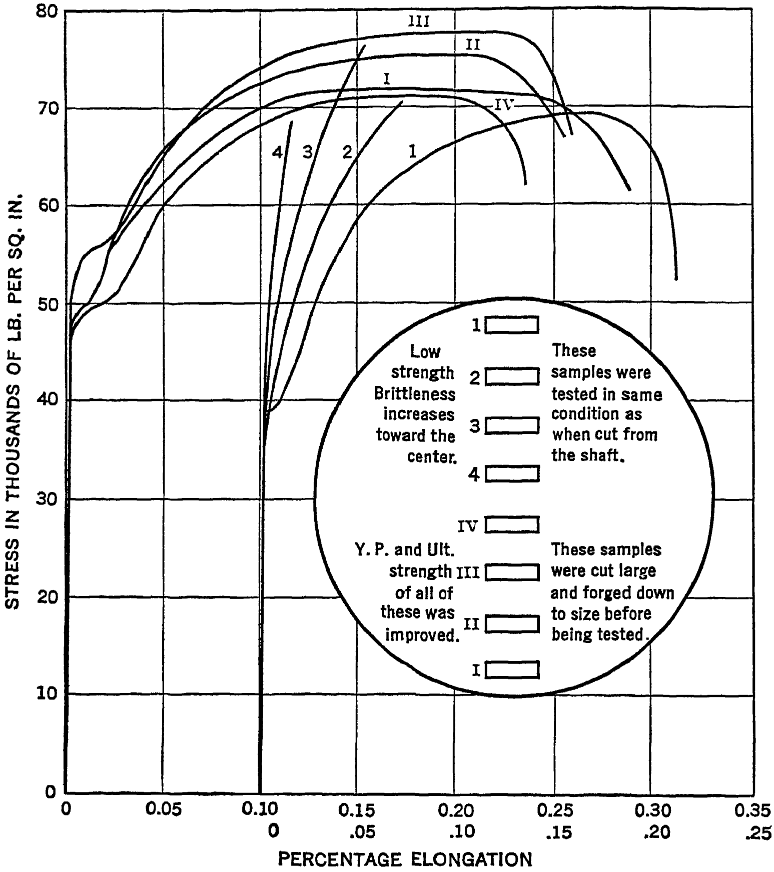


Figure 115. From Results of Tests of Shaft of U. S. S. *Dolphin*

below, the critical temperature when the last work is done upon it.

Effect of Hot Work on the Properties of Steel and Iron.—It is often rather difficult to decide just how much the properties of a steel are affected by the hot work done on it and how much of the effect is produced by the hardening and tempering which are always present.

The greatest amount of work is generally done on the smallest sections or on the outside of a heavy section and that is where the most rapid cooling takes place. However, there are plenty of examples where great differences occur and they indicate quite clearly the beneficial results of hot working.

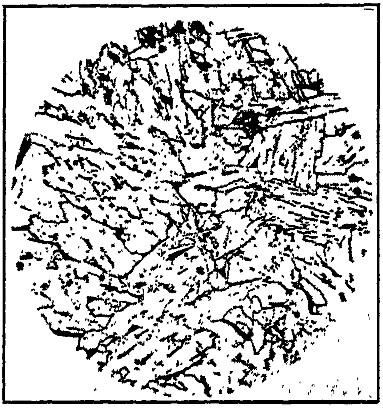
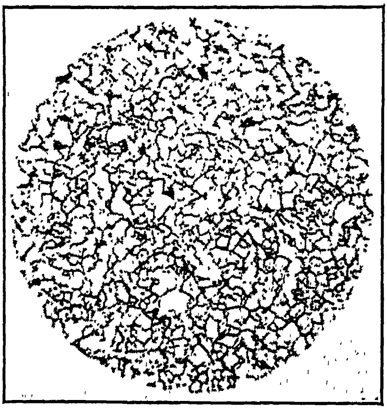


Figure 116. Low Carbon Steel as Cast



(Courtesy of American Steel & Wire Co.)

Figure 117. Low Carbon Steel after Hot Working

Figure 115 shows the results of tests of samples of a forged 16-in. shaft which broke soon after it was installed. Four samples were tested as cut from the shaft. Four others were forged after cutting out. The gain in ductility is apparent.

The difference in physical structure between naturally cooled and properly hot-worked low carbon may be noted by examination of the photomicrographs of Figures 116 and 117.

Effect of Cold Work on Structure of Steel.—Cold working of steel, or reduction of area at temperatures well below the critical temperatures, results in distortion of the grain, varying in amount in proportion to the force applied. This distortion remains unless annealing is resorted to, because the rigidity of the metal is so great that it overcomes the tendency to return to the normal condition. (See Figures 118 and 119.)

If the process of cold working is carried beyond the limits of ductility of the metal, rupture will take place resulting in the ruining of the material. Figure 120 shows such a fault in the material of the head of a cold-headed, round head screw.

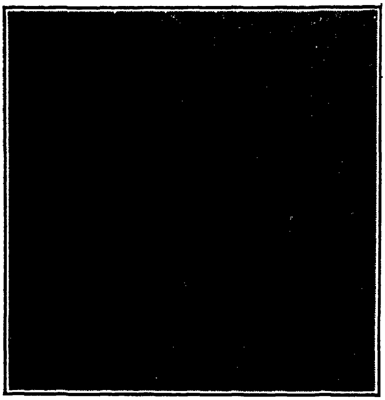


Figure 118. Low Carbon Steel Annealed
Original magnification 100 times

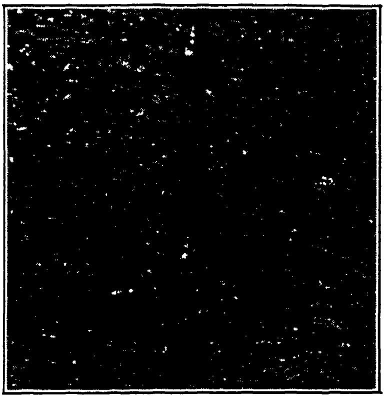


Figure 119. Annealed Low Carbon Steel after Severe Cold Working
Original magnification 100 times

Figure 121 shows the effect of excessive cold drawing of wire.

Although it has been generally supposed that it was necessary to heat cold-worked steel to above the critical temperature in order to remove the effect of cold working, it has been shown conclusively that heating to a little over 600° C., well below the critical range, will completely remove internal stresses from the ferrite and cause equiaxed grains to reform, leaving only the pearlite distorted.

In pure iron, or very low carbon steel, there is a danger in low temperature annealing, for under certain conditions of temperature and severity of cold working, these materials exhibit phenomenal grain growth, resulting in coarse-grained,

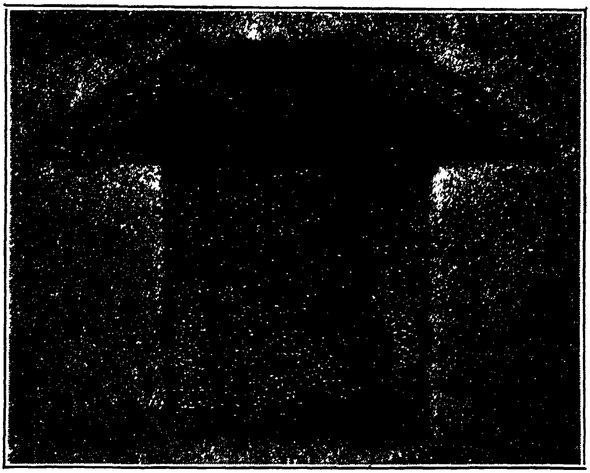
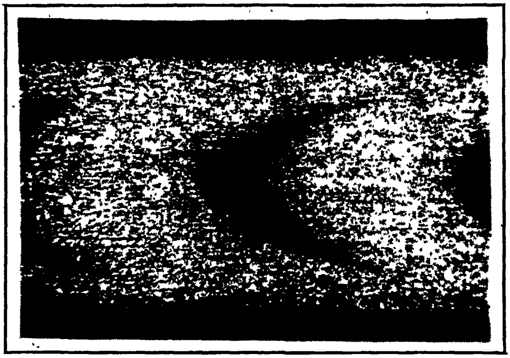


Figure 120. Cross-Section of Cold-Headed Bolt Deep Etched to Show Strain or Flow Lines

At the left, just under the shoulder, internal rupture has actually occurred. These heads will pop off under practically no strain.

Original magnification about 8 diameters



(Courtesy of American Steel & Wire Co.)

Figure 121. Internal Rupture in Wire Caused by Excessive Cold Working

Original magnification 50 times

weak, and brittle sections. This phenomenon is sometimes known as "Stead's brittleness" from J. E. Stead who first investigated it. Presence of slag or carbon in the form of pearlite seems to stop this tendency to grain growth, and consequently it does not occur in wrought iron or steel of over 0.15% carbon.

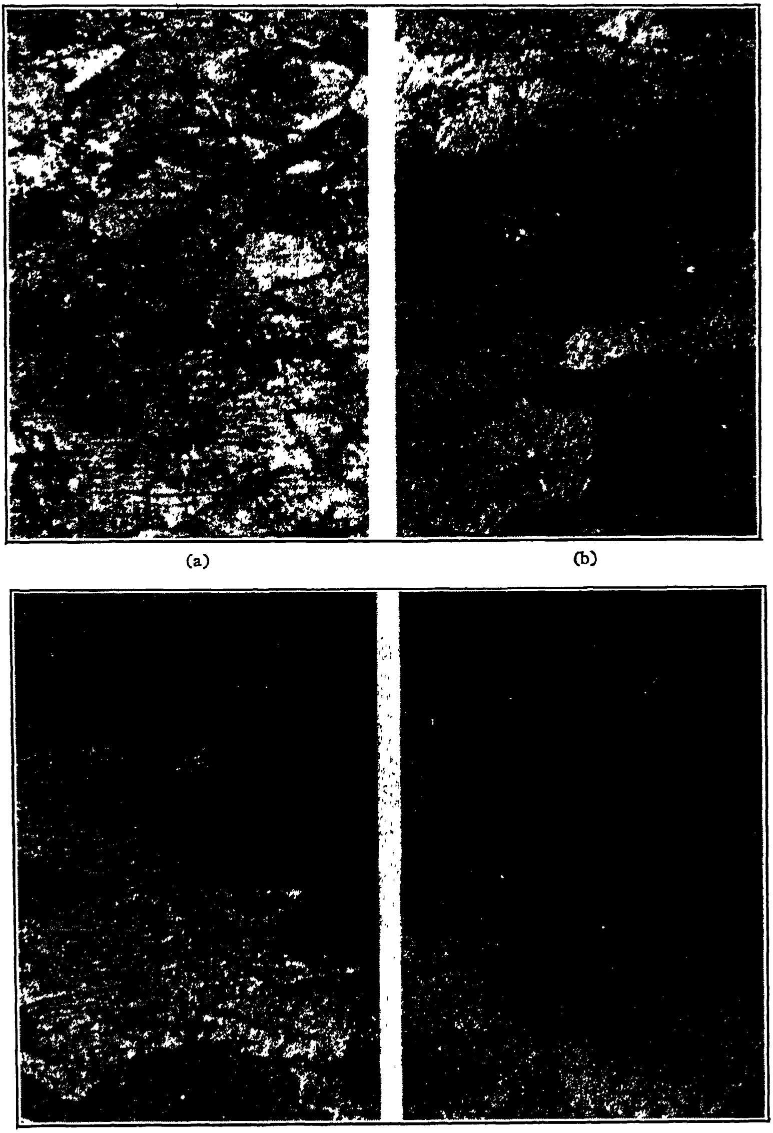
Figure 122 shows a material in which there was great variation of the amount of cold working. The subsequent annealing shows the great difference in the grain growth in different parts of the section.

Methods of Cold Working and Effect on the Physical Properties.—Cold work may be produced in any way which stresses the material beyond the yield point, thereby resulting in the plastic flow of the metal. Cold rolling, cold pressing, cold drawing, cold twisting, and cold punching are the most common methods.

Depending on the amount of cold working, and the resultant distortion, the yield point may be raised to nearly equal the ultimate strength, and on account of the reduction in area, the ultimate strength per unit area is also increased. As the strength increases, the ductility decreases, and there is a loss of toughness in cold-worked materials. They are not well adapted for shock resistance.

Successive operations of cold working by drawing and process annealing and "patenting" which is an annealing process, produce almost unbelievable results. Thus we find annealed steel wire with a strength of 50,000 to 60,000 lb. per sq. in. while the hard-drawn, low carbon steel may run to 100,000 lb. per sq. in. and 0.80% carbon, hard-drawn wire has been produced in small sizes with a strength as high as 447,000 lb. per sq. in.

Case Carburizing and Case Hardening.—For certain special mechanical elements steel is sometimes required which is very hard, to resist abrasion and wear and yet tough enough to



(a) (b)

(c) (d)

Figure 122. Variation in Grain in Cold-Drawn Steel Thimble About 3 in. Deep. Partial annealing caused great variation in grain growth

(a) was at the open end. (b) was on the side, near the open end. (c) was on the side, near the closed end. (d) was at the closed end of thimble.

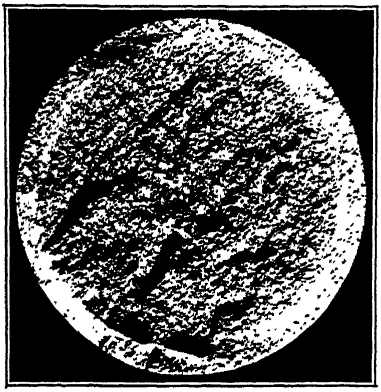


Figure 123. Case Carburized Sample of Rough Fracture, Shows Depth of Case

Original magnification 5 times

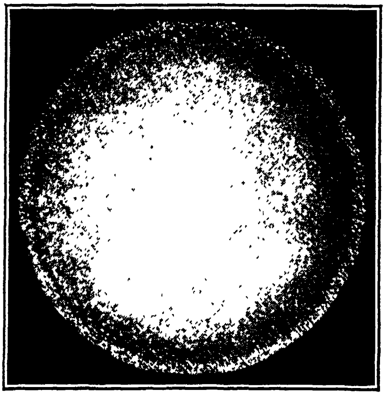


Figure 124. Case Carburized Sample Polished and Etched, Shows Carburized Ring

Original magnification 4½ times

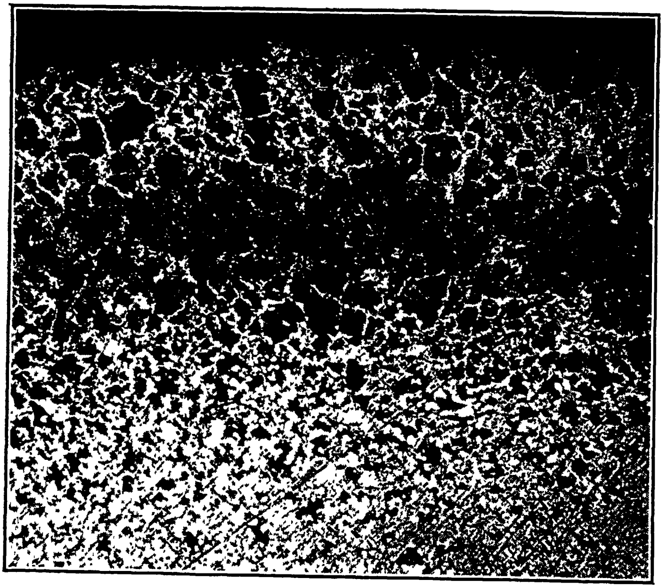


Figure 125. Etched Case Carburized Sample, Shows High-Carbon Exterior, Eutectoid Ring, and Low-Carbon Core

Original magnification about 50 times

stand considerable shock. This is hardly a possible combination for ordinary carbon steel of uniform carbon content. However, low carbon steels, when packed in a carbonizing medium, finely ground, and raised to the proper temperature, about 900° to 950° C. or about 1,700° F. in an atmosphere of CO_2 will absorb considerable carbon. This absorbed carbon penetrates slowly and the depth of penetration increases with the time which it is held at the carbonizing temperature. The carbon content increases from that of the original on the inside of the case to high carbon on the outside. The thicker the case the higher the carbon on the outside.

Figures 123 and 124 show the relation of the carburized ring to the total cross-section. Figure 125, at higher power, shows quite clearly the variation in carbon content.

By first heating above the critical temperature of the low carbon core and quenching, then heating above the critical temperature for the high carbon case and quenching for hardening, and subsequent drawing in the proper amount, a material with a fine-grained hard case with a softer and much tougher core may be easily produced.

This process is much in use, both with plain carbon steels and certain of the alloy steels.

Alloy Steels.—Alloy steel is defined as " steel which owes its distinctive properties chiefly to some element or elements other than carbon, or jointly to such other element and carbon."

The simplest alloy steels are those whose properties are dependent on only one element other than iron and carbon. These are called *ternary alloys* or three part alloys. *Quaternary* alloys contain two influential elements other than iron and carbon, and complex alloys contain several, or at least more than two influential elements other than iron and carbon.

Most alloy steels bear names which indicate the important element or elements which are responsible for their peculiar properties.

The principal alloys in these classes are listed below:

TERNARY ALLOY STEELS	QUATERNARY ALLOY STEELS	COMPLEX ALLOY
Nickel Steel	Chrome-Nickel Steel	Various combinations of the other alloying metals
Chrome Steel	Chrome-Vanadium Steel	
Vanadium Steel	Chrome-Manganese Steel	
Manganese Steel	Chrome-Tungsten Steel	
Tungsten Steel	Nickel-Manganese Steel	
Silicon Steel	Nickel-Tungsten Steel	
Molybdenum Steel	Nickel-Silicon Steel	
	Tungsten-Manganese Steel	
	Manganese-Silicon Steel	
	Chrome-Silicon Steel	

General Effect of Addition of Alloying Element to Carbon Steel.—The effect of adding an alloying element to carbon steel is, in general:

1. To lower the critical temperature.
2. To slow up the transformation from one phase to another.
3. Improvement of physical properties. Increased strength and toughness or more resistance to heat, or corrosive action.
4. An effect on the rate of grain growth at elevated temperatures.

Effect of Lowering the Critical Temperature.—Figures 126 and 127 have been constructed to show the general effect of the depression of the critical temperature. These diagrams show what type of structure may be expected from alloys of certain types when slowly cooled to atmospheric temperature.

The main difference between steels which follow the scheme of Figure 126 and those of Figure 127 is that in the "A" group the alloying element, or its carbides, become dissolved in the gamma iron and the richer alloys show the polyhedral grains of austenite, while on those of the "B" group the carbides will not remain in solution but appear as rounded or angular modules in the surrounding matrix.

In short, the material may show structure either austenitic, martensitic, or pearlitic on slow cooling according to the relation of the special element and carbon, and in addition, the so-called cementitic steels will contain the particles of free carbide surrounded by a matrix of one of the other constituents.

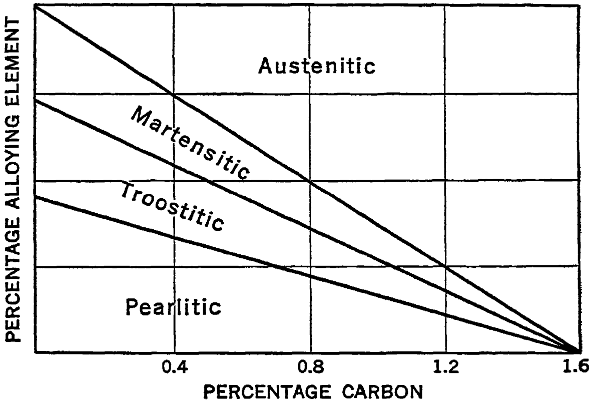


Figure 126. Alloy Steel Type A

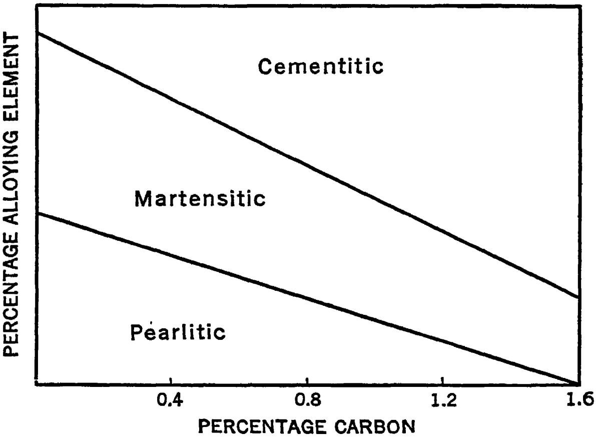


Figure 127. Alloy Steel Type B

Pearlitic steels are in general the steels containing a small percentage of the alloying element. They respond to the same treatments as ordinary carbon steels, namely, annealing, hardening, tempering, and case hardening. Their critical temperature is, in general, lower than that of carbon steel. It should be determined for each steel. Heat treatment requires a temperature considerably above the critical, and a soaking period longer than is customary for carbon steels because the transformation into solid solution is slower.

A peculiar situation arises in case carburizing such steels, for, as the carbon content increases, the case of the material passes from the pearlitic to the martensitic or even to the austenitic zone. It is thus possible to get a tough pearlitic core and a hard martensitic case without quenching.

Martensitic special steels are quite stable below the critical temperature. So much so, in fact, that they are not readily affected by ordinary tempering treatments. Some special steels which are ordinarily martensitic may be made pearlitic by very slow cooling. Such steels would be machinable but could readily be made hard by subsequent heating and air cooling.

Austenitic steels are theoretically stable at all temperatures and therefore would not respond at all to heat treatment. However, some such steels, if cooled very slowly, become martensitic to some degree, and therefore become brittle and regain some magnetic properties. Also slow cooling sometimes causes the carbides to come out of solution to some extent, thereby greatly reducing the toughness. Heating will cause the reabsorption of the carbides and the complete transformation to austenite and quenching will retain them. Austenitic steels which have received this treatment are said to be "water toughened."

Cementitic steels contain many particles of the carbide embedded in a matrix which may be austenitic or pearlitic or any of the intermediate stages according to the rate of cooling. In order to produce the most desirable results, it is often necessary to cause the reabsorption of these particles, at least in part. Heating to a high temperature, about 1,000° C. or 1,850° F. followed by relatively quick cooling, is necessary. For some steels, air cooling is quick enough.

Slowing Up of the Transformation.—This effect, which is much more marked in the case of some alloys than with others, is of the greatest importance in the heat treatment of heavy sections. The slower the rate of transformation, the more chance there is to depress the temperature within heavy masses, to such a point that the transformation will be checked entirely by the rigidity of the material and it therefore becomes possible to get great penetration of heat treatment. Ordinary carbon steels go through the transformation range so rapidly that very deep penetration is impossible even with the most drastic quenching methods.

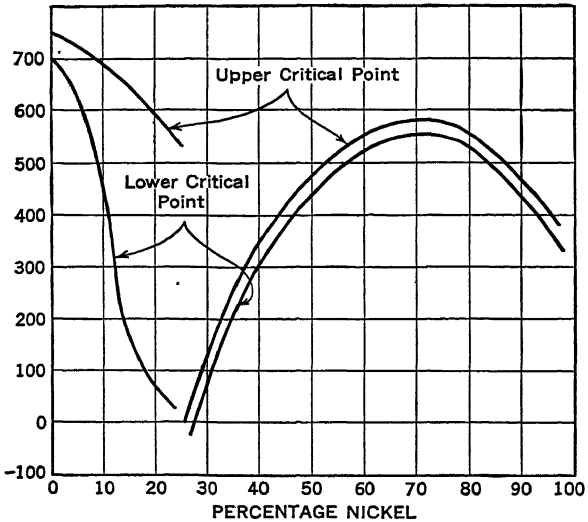
Improvement of physical properties is discussed briefly under the different types of alloy steels.

An Effect on Rate of Grain Growth at Elevated Temperatures.—As has already been pointed out, ordinary carbon steel tends to excessive grain growth at elevated temperatures and forging operations must be rapid and drastic to keep the growth from progressing and the temperature must be reduced before the finishing of the forging process or large grain will result. However, by the addition of some alloying element such as, for instance, vanadium, this tendency to grain growth is much reduced and it is possible to finish forgings from such material at a more elevated temperature with much less danger of bad structure.

It is beyond the scope of this text to go deeply into the peculiarities of heat treatments of the host of alloy steels on the market, but it is safe to say that practically all the treatments are used in conjunction with the alloying elements to modify the natural behavior of the iron-carbon system, so that the iron-carbon system is the basis and starting point for nearly all.

Quaternary and *complex steels* may be in any of the stages already discussed, but the proportions of the various elements present complicate the equilibrium diagram, and the formation of solutions and carbides to a considerable extent. Most of the successful steels of this type that have been developed have been the result of trial rather than by analysis and prediction from study of the very complex equilibrium diagrams. In most cases the practice is far ahead of the theory.

Effect of Various Alloying Elements on the Properties of Steel.—Nickel apparently dissolves in iron in all proportions and in both the alpha and gamma phases. As the nickel content is increased the critical temperatures are depressed, but the critical temperature on cooling is depressed much more rapidly than that on heating, so that the hysteresis gap becomes great and such steels are said to be irreversible. At about 25% nickel the upper critical point suddenly drops to match that of the cooling and for higher percentages the changes are reversible. Figure 128 shows this phenomenon clearly.



(Courtesy of A. Sauveur)

Figure 128. Influence of Nickel on the Critical Points of Iron

Low nickel steels of about 2% to 4%, are important for structural purposes, forgings, machine parts, steel rolls, etc., but their best qualities are not brought out without heat treatment.

When properly treated there is a great increase in elastic limit and tensile strength without too great sacrifice of ductility. Where high strength and light weight, combined with great toughness, is required, nickel steels are of great value. One disadvantage of nickel steel is its tendency to segregation and flaws.

Nickel steels with 12% to 22% nickel are very hard and brittle and not machinable.

Nickel steels of 22% to 25%, with proper carbon content, have been used where exposure to corrosion is severe.

Nickel steel of 36%, called Invar, is remarkable in that it possesses at ordinary temperatures a coefficient of temperature expansion of about zero, while 42% nickel steel has about the same temperature coefficient of expansion as glass and is called platenite.

Low nickel steels are widely used for case-hardening steels.

Chromium Steels.—Chromium forms double carbides with iron and tends to produce cementitic steels. The effect of chromium on the critical temperature has been in some dispute. It probably has little if any direct influence, any noticeable effect being caused by the influence of the carbides present, and their variable tendency to solution at different elevated temperatures. Chromium seems to slow up the transformations and therefore is of great value in securing great penetration of quenching effects, making it possible to harden and temper very heavy sections such as armor plate, for instance. Case-hardened chrome steels yield very hard cases, but the core is apt to be coarse and requires secondary treatment.

Chromium is of great value combined with other elements in quaternary or complex steels as will be indicated later. It is seldom used in amounts of over 2% or 3% except in special steels.

Vanadium Steels.—Vanadium is beneficial to the physical properties of steel up to about 1%. Owing to its high cost, it is seldom used in amounts exceeding 0.2%. Vanadium is one of the most powerful alloying elements, and it enters into both the ferrite and the pearlite. It enters into the cementite with iron forming a double carbide and produces a marked hardening and toughening effect. Vanadium materially reduces the tendency to grain growth and vanadium steels are not so apt to be spoiled by overheating.

Vanadium steels combine high strength with considerable ductility and therefore exhibit great resistance to shock loading.

Manganese Steel.—The term manganese steel is generally applied to steels containing about 11% to 14% manganese, and from 0.8% to about 1.5% carbon. When such steel is cast in ingot form it is very hard and brittle, and no carbon steel will cut it. However, on heating to 1,000° C. (1,832° F.) followed by quenching in water, the material is rendered much tougher and much more ductile, although it is still very hard in certain aspects. Manganese steel is very fluid when molten and sound castings are produced. Water toughened manganese steel is used for switch points, frogs, crossovers, curved rails, etc., and for jaws of stone crushers and, in fact, anywhere where there is combined peaning action and abrasion. Tractor shoes on stony gravel road will wear much longer if made of manganese steel, but there is little advantage on sandy clay.

The peculiarity of such steel seems to be that the tough austenitic steel becomes changed to a hard, wear-resisting skin of martensite under peaning action. As the hard surface is worn down, more immediately forms. Curved rails made of this material have lasted years, where the best carbon steel rails went out in less than a month.

Manganese is present in appreciable quantities in all commercial steels, but unless there is considerably more than 1%, they are not considered as manganese steels.

Steels containing low carbon and 2% to 6% of manganese and slowly cooled remain pearlitic and undoubtedly would possess some commercial value. Since it is necessary to introduce the manganese in the form of ferromanganese, the ordinary material produced in the blast furnace, therefore high in carbon, is not suitable for low carbon steel. However it is possible to produce low carbon ferromanganese in the electric furnace, and it is quite possible that improvements in the practice of steel-making will direct more attention to this material.

Tungsten Steel.—Tungsten, in small quantities, appears to raise rather than lower the critical points in steel; but in larger percentages, the steel becomes cementitic and then the lower critical temperature on cooling becomes very much affected, depending on the temperature from which the material has been cooled. There appear to be two critical temperatures if the metal is cooled from a temperature between 1,000° C. and 1,100° C. If heated to temperatures slightly below 1,000° C., only the one appears. This effect of tungsten is chiefly what causes the remarkable properties of self-hardening tool steels.

The ternary alloy tungsten steel is very little used, but the alloy of about 0.6% carbon, and 6% tungsten is used for permanent magnets. These magnet steels are hardened and then soaked at the temperature of boiling water for a long time. Such steels are very stable in their magnetic properties.

Silicon Steel.—Silicon in amounts above 5% tends to the production of free graphite. As long as the silicon is kept below 5%, however, the steel is pearlitic and closely resembles nickel steel in its properties.

When 1% or 2% of silicon is combined with from 0.1% to 0.4% carbon, the result is what might be classed as a high-strength structural steel. Its elastic limit is very high as compared with ordinary carbon steel of equal carbon content. However, it is rather hard and presents considerable difficulty in rolling.

The most valuable silicon steel is the one which is made particularly for use in electrical machinery and which was developed by Hadfield in England and patented in this country in 1907. Hadfield's silicon steel contains about 3% of silicon and the smallest possible amounts of carbon, manganese, and other impurities. This steel acquires its remarkable magnetic properties (very high permeability and low core loss) only after a special heat treatment. It is heated to between 900° C. (1,652° F.) and 1,100° C. (2,012° F.), cooled quickly to atmospheric temperature, reheated to between 700° C. (1,292° F.) and 850° C. (1,562° F.), and cooled very slowly. Sometimes it is again heated and cooled very slowly from about 800° C. (1,470° F.). It is used for pole pieces of dynamos and for transformer cores.

Molybdenum Steel.—Molybdenum has about the same effect, in general, as tungsten, but it is supposed to be about four times as powerful. It is said to produce a somewhat finer grain than tungsten.

Quaternary Alloy Steels.—Only a brief statement of the most important properties of quaternary alloy steels is given in the following paragraphs:

Chrome-Nickel Steels.—These steels owe their commercial value to very high strength, elastic limit, and hardness combined with good ductility, thus securing great toughness. All this depends on the proper heat treatment. Chrome-nickel steels are not quite so hard but are much tougher than simple chrome steels and are easier to heat-treat. For best results they require a rather complex heat treatment. Oil quenching is generally used.

The Mayari ores of Cuba contain enough chromium and nickel so that steels smelted from these ores have given very good results. Chrome-nickel steels are much used for automobile shafts and gears, and also for large axles and shafts.

Case-hardened, high chrome-nickel has been used for heavy armor plate, also for protecting deck coating and projectiles. For this latter purpose a very small amount, about 0.1%, of vanadium is often introduced.

Quaternary Vanadium Steel.—Sauveur says that "the introduction of small amounts of vanadium into the various special steels has been strongly urged and nickel-vanadium, chrome-vanadium, chrome-nickel-vanadium, and chrome-tungsten-vanadium steels have been used. It is claimed that the presence of a small amount of vanadium (less than 0.50%) increases the soundness of castings and the freedom from occluded gases." It certainly adds to the desirable physical qualities of forgings such as strength, resilience, ductility, and others.

Vanadium steels properly quenched are relatively so tough as not to require tempering. For most uses, however, they are quenched and drawn.

Chrome-vanadium steels are much used for automobile work, and for any place where high strength and resilience are required with minimum weight.

Chrome-vanadium steels may readily be case hardened taking a glassy, hard surface and a fine-grained, tough core. This property renders them valuable for dies and bearing raceways, and for pins for heavy and rough duty chains, such as truck and tractor chains.

High Speed Steels.—During the last 15 or 20 years, a line of steels has been developed which retain their hardness up to a red heat. They were developed particularly to stand the high heat produced at the point of a cutting tool used in rapid removal of metal in machine tools.

As may be suspected, tungsten forms the basis of this type of alloys. They generally contain 15% to 20% tungsten, 3% to 5% of chromium, 0.5% to 2.0% of vanadium, and

0.60% to 0.80% carbon. Molybdenum is sometimes used to replace the tungsten.

In hardening high-speed steels they are heated nearly to the fusion point and cooled in oil, or in molten lead, followed by air cooling, if considerable toughness is required. They may be annealed for machining by soaking for a long time just above the critical range for carbon steels, followed by very slow cooling.

Heat Resistant and Corrosion Resistant Steels.—On account of a demand for strong material to withstand high temperatures, and also for materials to resist various corrosive agents, a great variety of steels and other materials have been developed recently. Practically all of these steels have a high chromium content around 13% to 15%. Some run as high as 27% and some as low as 2%. A few have no chromium, some have nickel, some have silicon, and other have manganese.

The Crucible Steel Co. has developed an interesting and valuable series of steels called "Resistal" steels. These vary from 0.15% to 0.70% carbon: 1.25% to 3.25% silicon: 22% to 36% nickel: 5.5% to 27.5% chromium, and the remainder iron. They possess wonderful resistance to corrosion, and to deleterious effects of high temperature. The Midvale Steel Company has a similar series of steels in which there is no nickel but about 0.50% manganese instead.

The A. S. T. M. has published a comprehensive review of this class of material.

General Effect of Alloys on Hardness, Strength, and Ductility of Steels.—In the annealed state alloy steels are generally somewhat harder and stronger than carbon steels of the same carbon content, mainly because of the more finely divided pearlite or the condition of solution of the alloying element in the iron.

In hardened steel, carbon in proper amounts produces as hard a steel as a combination of carbon and some other elements, but the hardness and strength combined with any great degree of ductility are far less with carbon steel than with most of the useful alloy steels.

About the highest strength possible in carbon steel combined with an elongation of, say, 5% would be about 180,000 lb. per sq. in., while some alloy steels will have a strength of say 240,000 lb. per sq. in. with a very much higher elongation (15% to 20%). The advantages of alloy steels are:

1. Increased strength in annealed state.
2. Increased possible toughness, i.e., high strength and high ductility in treated state.
3. Increased resistance to change in properties due to high temperature.
4. Increased resistance to corrosion.
5. Miscellaneous minor advantages.

TABLE 9. PROPERTIES OF WROUGHT IRON

Size of bar in diameter	4	3	2	½	¼
Area of pile—sq. in.	80	80	72	9	3
Bar, per cent of pile	15.7	8.83	4.36	2.17	1.6
Tensile strength—lb.	46,322	47,761	48,280	52,275	59,585
Elastic limit—lb.	23,430	26,400	31,892	39,126	

TABLE 10. STRENGTH FOR CARBON STEELS

Trade Name	Carbon %	Tensile Tests of Annealed Metal		
		Ultimate Strength lb. per sq. in.	Elastic Limit lb. per sq. in.	Elongation %
Very mild steel	0.5 –0.15	45,000– 54,000	27,000–33,500	34–28
Mild steel	0.15–0.25	54,000– 67,000	33,500–40,000	28–25
Low carbon steel	0.25–0.40	67,000– 78,000	40,000–45,000	25–22
Medium carbon steel	0.40–0.60	78,000– 90,000	45,000–54,000	22–18
High carbon steel	0.60–0.70	90,000–105,000	54,000–63,000	18–14
Spring steel	0.70–0.80	105,000–120,000	63,000–72,000	14–8
Pearlitic or eutectoid steel	.085	140,000	78,000	6
High carbon tool steel	85–150	150,000	80,000	5

TABLE 11. COMPOSITION AND STRENGTH OF VARIOUS STEELS

No.	Material	Heat Treatment	C	Approximate Analysis				Elastic Limit (E)	Tensile Strength	Elongation in Quantities %	Reduction of Area % (R)	Alternations (A)	Quality E × R × A ÷ 10^6
				Mn	Cr	Ni	V						
				ELASTIC LIMITS, 30,000 TO 60,000									
1	Wrought iron	R.	0.05	0.05				32,020	49,450	42.5	53.8	583	1004
2	Mild Va steel	A.	0.11	0.31			0.19	32,120	54,400	44.0	60.1	1111	2143
3	Old plate	R.	0.24	0.42				58,160	70,840	25.5	53.4	612	1901
4	Mild steel	A.	0.18	0.40				39,460	61,850	35.0	62.6	871	2152
5	Mild steel	O. T.	0.18	0.40				45,390	77,310	33.0	64.0	777	2258
6	Forging steel	A.	0.26	0.28				43,010	55,990	34.0	63.4	1415	3858
7	Forging steel	O. T.	0.26	0.28				52,230	81,370	28.0	65.3	1175	4008
8	Va case hardening	A.	0.15	0.25	0.30		0.12	44,790	55,990	45.0	69.0	1958	6051
9	Cr-Ni steel	A.	0.36	0.34	0.95	1.70		56,520	81,370	32.0	68.5	978	3787
10	Steel casting	A.	0.18	0.65				34,690	58,800	28.0	44.9	269	419
11	Va steel casting	A.	0.19	0.60			0.076	44,340	70,250	25.5	44.9	850	1671
12	Cr-Va casting	A.	0.57	0.68	0.75		0.16	52,330	92,900	16.0	20.5	656	704
				ELASTIC LIMITS, 60,000 TO 100,000									
13	Ni forging steel	A.	0.21	0.45		3.70		61,140	79,700	30.0	62.5	746	2851
14	Ni forging steel	O. T.	0.21	0.45		3.70		77,140	98,470	25.0	65.3	664	3345
15	Cr-Va forging	A.	0.26	0.50	1.00		0.16	61,920	92,900	25.0	57.3	1608	5706
16	Spring steel	A.	1.00	0.30				63,800	125,000	8.5	15.2	1260	1222
17	Cr-Va spring	A.	0.40	0.77	1.22		0.19	67,520	100,000	26.0	61.7	1406	5858
18	Cr-Ni-Va steel	A.	0.30	0.27	1.51	3.45	0.085	69,140	96,880	28.5	68.5	507	2402
19	Ni-Va steel	A.	0.24	0.72		3.40	0.15	79,260	99,700	25.0	64.0	798	4048
20	Cr-Ni-Va steel	A.	0.57	0.27	0.93	2.04	0.07	95,150	129,100	21.0	49.8	983	4659
21	Cr-Ni steel	T.	0.37	0.34	0.89	1.70		86,080	102,700	22.0	63.8	702	3855
				ELASTIC LIMITS, 100,000 AND OVER									
22	Spring steel	O. T.	1.00	0.30				101,000	186,300	9.5	16.1	561	912
23	Cr-Va spring	O. T.	0.40	0.77	1.22		0.19	195,300	208,500	10.0	36.3	480	3403
24	Cr-Va forging	O. T.	0.30	0.50	1.00		0.16	141,600	151,750	16.0	56.2	717	5705
25	Ni-Va steel	O. T.	0.24	0.72		3.40	0.15	129,900	134,600	18.0	64.8	626	5270
26	Cr-Ni-Va steel	O. T.	0.30	0.27	1.51	3.45	0.085	152,300	159,900	17.0	58.9	487	4369
27	Cr-Va spring	O. T.	0.40	0.77	1.22		0.19	183,400	187,600	14.0	50.6	634	5883
28	Cr-Ni steel	T.	0.36	0.34	0.95	1.70		134,500	150,300	15.5	53.5	579	4166

Notes. Static tests made on samples ½ in. diam. × 2-in. long. Dynamic tests made on the Landgraf-Turner alternating impact machine (old form). The quality figure is the product of: Elastic limit, representing useful strength; reduction of area, representing static ductility; dynamic figure, representing fatigue-resisting property—divided by 1,000,000 = E × R × A ÷ 10^6.

Heat treatment, R, raw: A., annealed: O. T., oil tempered: T, tempered. Nos. 9 17, 18 20, 21 26, 27, 28 were crucible steels, the others open hearth. (Reprinted by permission from Mechanical Engineers Handbook by Robert T. Kent.)

Physical Properties of Various Irons and Steels With Various Treatments.—Mechanical work is important for wrought iron not only to refine the grain, but to distribute the metal and slag and produce the so-called "fibrous structure" characteristic of wrought iron. The amount of reduction from the pile to the bar has a notable effect on the strength as shown in Table 9.

The modulus of elasticity of steels does not vary with carbon or treatment; it is about 29,000,000 to 30,000,000 lb.

Nitriding.—Since this text was started, a new process of case hardening, by exposure to ammonia gas, has come rapidly to the foreground. Steel to be nitrided is exposed to ammonia gas at 500° F. or a little above, and it absorbs the nitrogen to form a hard case of iron nitride. This has the advantage of producing a hard, wear-resisting surface of great durability with very little danger of warping or cracking. Its application to commercial production has been very rapid.

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CHAPTER 8

NON-FERROUS METALS AND ALLOYS

Copper.—Nearly all copper is extracted by smelting in a special type of blast furnace using coke as a fuel. The product of the blast furnaces is a sulphide "matte." Removal of a large portion of the iron and sulphur is accomplished by placing the molten "matte" in a converter and oxidizing by an air blast which enters just above the bath. The crude copper ("blister copper") thus formed is cast into small pigs.

Refining of crude copper may be accomplished either by smelting in a reverberatory furnace or by electrolysis.

Fire refining gives crude copper the malleability, ductility, and toughness essential in plates, tubes, and wire. It is also used to refine copper to be used in making alloys.

Electrolytic refining is used when an especially pure grade is wanted for special high-grade alloys or electrical purposes.

Copper for electrical purposes should contain less than 0.1% of impurities (silver being counted as copper). Copper for castings generally has impurities lower than 1%.

Commercial Grades of Copper.—Three grades of refined copper for rolling have ordinarily been recognized, viz.: Lake, electrolytic, and arsenical. However, there seems to be little distinction between the lake and electrolytic grades, inasmuch as their physical properties and chemical composition are nearly identical. Both will average over 99.88% copper (plus silver). The arsenical copper contains from 0.2% to 0.5% arsenic and is chiefly used for firebox plates and stay bolts because of its somewhat greater strength at higher temperatures and its greater resistance to the corrosive action of the hot gases.

Another lower grade of copper called "casting copper," containing 98.5% copper or over is sold for foundry smelting.

Fabrication of Copper.—Copper may be forged or rolled either hot or cold; extruded or pierced when hot; drawn, stamped, or spun when cold. It can be brazed, soldered, or welded.

When copper has been severely cold-worked it loses its ductility, which, however, can be restored by annealing at a temperature of about 1,100° F.

Annealing should be carried out in a slightly oxidizing atmosphere. A reducing atmosphere at high temperature will produce brittleness.

Physical Properties of Copper.—

Pattern shrinkage allowance ¼ in. per ft.
Temperature coefficient expansion (0.00000926).
Young's Modulus of Elasticity 17,300,000 lb. per sq. in.

TENSILE PROPERTIES

	Annealed	Cold-Rolled or Drawn	Cast
Tensile Strength lb. per sq. in.	30,000–40,000	50,000–70,000	20,000–30,000
Elongation in 2 in.	40%–60%	2%–4%	25%–45%
Reduction of Area	40%–60%	2%–4%	

An examination of Figure 129 shows that it is very hard to control the strength and ductility of cold-worked copper through the annealing process. On the other hand, Figure 130 shows how easily these properties may be controlled by the process of cold working.

Uses of Copper.—The greatest proportion of copper is used for electrical conductors. Probably 20% to 30% goes into alloys and the remainder into sheets, condenser tubes, and other small tubes which have to withstand the action of certain kinds of corrosive agents and possess fair strength and flexi-

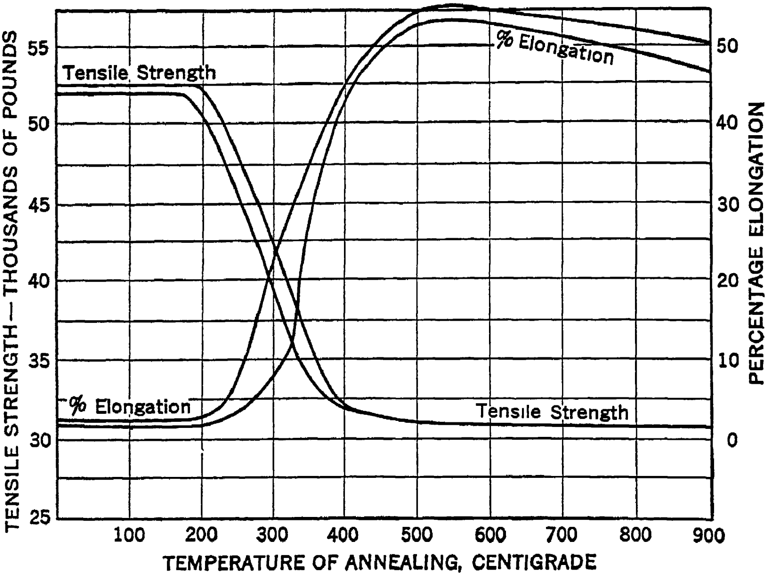


Figure 129. Tensile Strength and Elongation of Annealed Copper

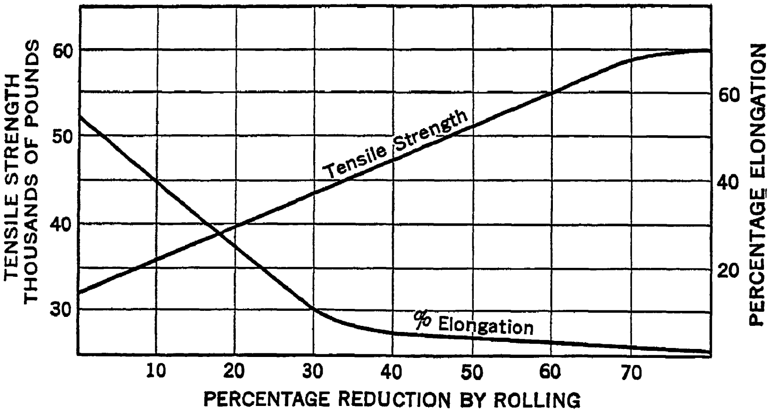


Figure 130. Tensile Strength and Elongation of Rolled Copper

bility. Some copper finds its way into art in the form of cast or hammered ornamental forms.

Zinc or Spelter.—The principal features in the extraction of zinc from its ores are the reduction of the sulphides and carbonates to oxide form and the subsequent distillation of the oxide. The oxide is reduced by mixing with coal and carefully controlling the temperature at a white heat. The zinc so formed is collected in condensers and run off from time to time, skimmed, and cast into molds. Zinc cast in this way is called spelter. Although most of the zinc made in the United States is pure enough for commercial use, if it is contaminated with lead or iron it may be somewhat refined by smelting at as low a temperature as possible, when a separation is effected though a difference in specific gravities.

Electrolytic refining is now carried on to a certain extent. The commercial grades are listed in Table 12.

TABLE 12. COMMERCIAL GRADES OF SPELTER

	Grade No.	Maximum Allowable Per Cent of			Lead + Iron + Cadmium Not to Exceed
		Lead	Cadmium	Iron	
High-grade	1	0.07	0.07	0.03	0.10
Intermediate	2	0.20	0.50	0.03	0.50
Brass Special	3	0.60	0.50	0.03	1.0
Brass Special	4	0.80	0.75	0.04	1.25
Prime Western	5	1.60		0.08	

Grades 1 to 4 must be free from aluminum.

Commercial Forms.—Zinc is not used in sand castings except alloyed with some other metal which predominates. However, it may be used in die castings, slush castings, or in special electrodes for batteries.

Zinc of suitable composition and under proper working conditions may be rolled or extruded, pressed, drawn, or stamped. A considerable amount is used as sheet zinc.

Zinc at present finds its application where softness, pliability, and ductility or a very mild temper are the desired characteristics. It is used as a lining for water tanks, for roofing as sheet roofing or shingles.

Although zinc will not rust it will not stand much attack of weak acids, and when used as a roofing in localities where there is much carbon dioxide in the atmosphere it rapidly corrodes.

Cold Working of Zinc.—Unlike most of the ductile metals, pure zinc cannot be rolled to a hard temper because the metal immediately recrystallizes at atmospheric temperature and so remains soft.

If it is desired to get some hardening effect, small additions of cadmium may be made, giving variations in tensile strength of perhaps 15,000 to 40,000 lb. per sq. in. This range is very low compared to that obtainable with other non-ferrous metals and alloys.

Tensile Properties of Zinc.—Ordinary cast zinc has a tensile strength of about 10,000 lb. per sq. in., but die cast zinc may have a strength of as high as 20,000 lb. per sq. in. on account of a much finer grain.

Zinc is rather plastic and has no well-defined yield point. The modulus of elasticity is rather indefinite on account of the tendency to plastic flow, but it probably is somewhere about 11,000,000 to 14,000,000 lb. per sq. in.

The tensile strength of soft-rolled, fairly pure zinc may be about 16,000 to 17,000 lb. per sq. in. if pulled slowly and tested in the direction of rolling, or about 23,000 lb. per sq. in. if tested transversely. But if the speed of pulling is increased to a high rate, the strength is increased by some 60%. This peculiarity is probably due to the fact that recrystallization has time to counteract the cold work at slow speed, but at high speed the rate of cold working is more rapid than the recrystallization.

Tin.—Tin is smelted at high temperature in a reverberatory furnace. It is refined by careful smelting and agitation to oxidize the impurities.

The best grades of tin carry less than 0.1% of impurities. Tin recovered from scrap may contain as much as 1% to 5% of impurities. Lead, antimony, and copper are the principal associated metals.

Uses of Tin.—Most of the commercial tin finds its way into alloys of various kinds, particularly the bronzes. Since it is highly resistant to atmospheric corrosion, it has been widely used as a coating for soft steel sheets.

Pure tin, or "bright" tin as it is often called, is used as a coating for sheets to be used in making tin cans, utensils, and hot air pipes for furnaces.

Roofing tin is made by coating steel sheets with a lead-tin alloy. It is commercially known as "terne" plate. Roofing tin may be single, double, or triple-coated.

A small amount of tin is made into tinfoil. Copper wire is often tinned to prevent corrosion.

Tin is about three times as heavy as iron but has a tensile strength of only about 2,000 to 5,000 lb. per sq. in.

Castings of tin shrink only about $1/12$ in. per ft.

Lead.—Lead is a very soft, malleable (but not very ductile) metal, nearly four times as heavy as iron. It is highly resistant to certain forms of corrosion, and is much used for water pipes where difficult bends have to be made. Lead is used as a lining for tanks and vats for certain chemicals and as a shield for protection against X-rays.

Some lead is cast into such shapes as storage battery grids, etc. Lead castings shrink about $5/16$ in. per ft. on cooling.

Lead may be rolled into very thin foil. It is formed into pipes by extruding the hot metal through dies.

Impurities reduce the softness and specific gravity. Magnesia, especially, has a decided hardening effect.

The strength of cast lead is 1,500 to 2,000 lb. per sq. in., but hard-rolled lead wire may reach 3,000 lb. per sq. in.

Copper Base Alloys—Brasses and Bronzes

The Brasses—Copper-Zinc Alloys.—The most useful brasses contain from 60% to 90% copper and 10% to 40% zinc. For certain purposes brasses as high as a 50-50 ratio have been used. However, the brasses richer in zinc than 45% to 50% become so hard and brittle as to be of little commercial use.

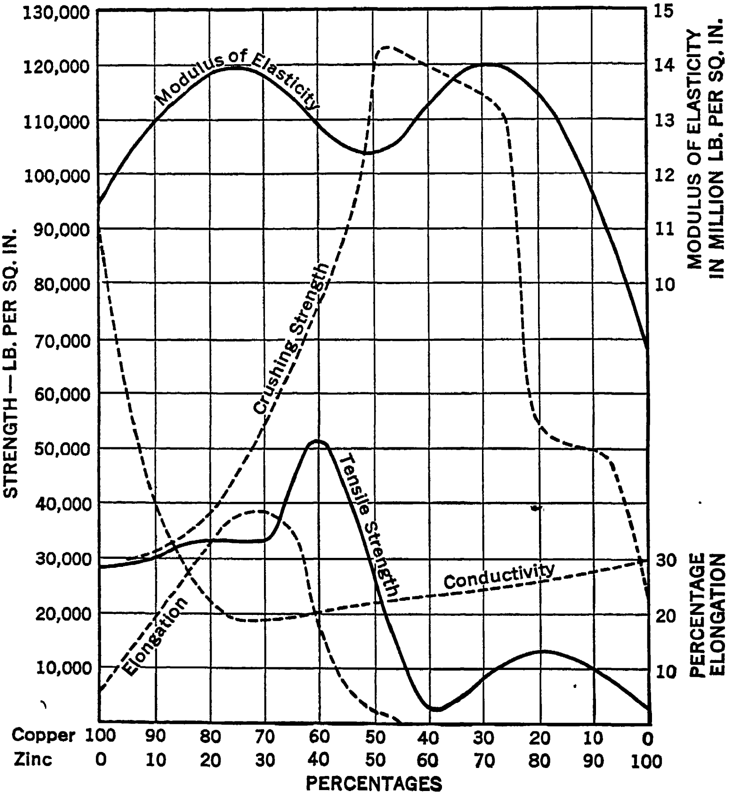


Figure 131. Properties of Cast Brass (From U. S. Test Board Reports)

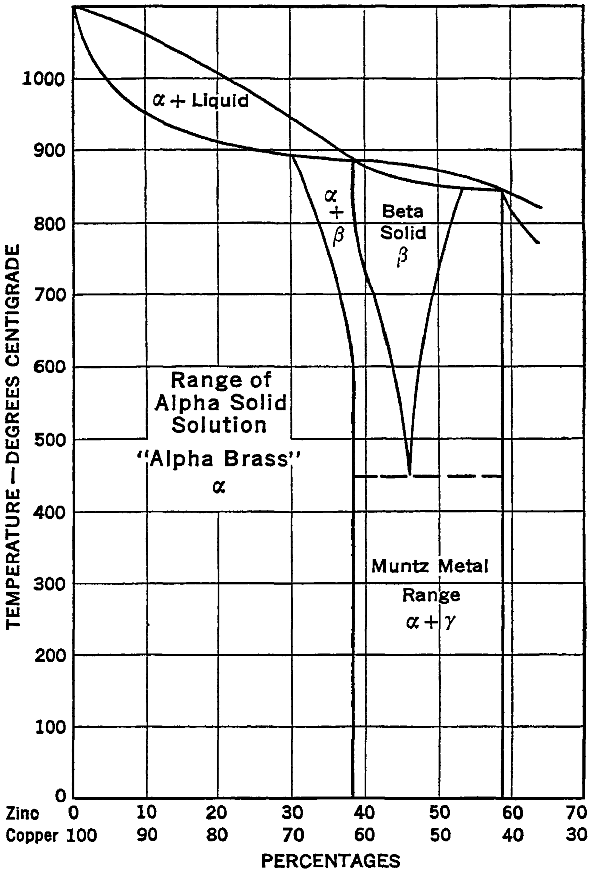


Figure 132. Equilibrium Diagram of Copper-Zinc Alloys (Taken from diagram in Rosenhain's Metallurgy)

As the percentage of zinc in brasses increases, there is a peculiar form to the curves showing the relative changes in physical properties. Figure 131 shows these relations.

The tensile strength curve is the most significant. It is seen that the line is nearly horizontal up to about 30% zinc, where it rises sharply and then dips again so that by the time the zinc content is as high as 60% the strength is negligible.

At the same time the ductility increases up to about 30% zinc and then drops to zero at about 50-50 composition. This shows that brasses of high zinc content are so weak and brittle as to be practically worthless.

To understand better this peculiar behavior it is necessary to study a part of the thermal equilibrium diagram. Figure 132 shows the high copper end of this diagram taken from the work of Shepherd and Carpenter.

This diagram, giving the equilibrium conditions for different temperatures and concentrations, indicates that up to about 38% the material will solidify into what is known as the "alpha" phase. This phase is a simple solid solution of zinc in copper and it is increasingly ductile in the cold, as the zinc content increases. After about 30% of zinc there is a tendency for more or less of the so-called "beta" constituent to form. This crystal form is stronger than the alpha, but ductile, to any extent, only while hot.

Progressing still further the "alpha" phase disappears and a new and much harder phase appears, called "gamma," which renders the material weak and brittle.

Comparing Figures 131 and 132, the reason for the peculiar characteristic of the strength curves at once becomes apparent.

Since the useful brasses are limited to those with less than 45% zinc, it is convenient to divide them into two classes, viz.: Class 1, alloys containing zinc up to about 36%; Class 2, alloys containing zinc between 36% and 45%.

Class 1. Alloys containing 36% or less of zinc. These alloys consist of grains or crystal aggregates made up entirely of the "alpha" solid solution phase and they are known, collectively, as "alpha" brasses. Alpha brasses are more or less easily rolled or drawn at atmospheric temperatures and are ordinarily referred to as cold-working brasses. Although some of the high copper brasses are sometimes used where electrical conductivity is important, the most widely used "alpha" brasses are the 70-30 and "two and one."

The first of these, 70% copper and 30% zinc, is usually known as "Cartridge brass," and the second is often called simply "brass."

Cartridge brass is very ductile and under mechanical and heat treatment becomes very homogeneous, stable, and unlikely to change its crystal form.

Aitchison and Barclay give the mechanical properties of Cartridge brass about as follows:

	Y. P. lb. per sq. in.	Ultimate lb. per sq. in.	Elongation %	Brinell Hardness
Chill casting	12,000	32,000	60–70	60
Hard-rolled sheet	40,000	60,000–80,000	10–15	150–200
Annealed	12,000	40,000–46,000	60–75	60

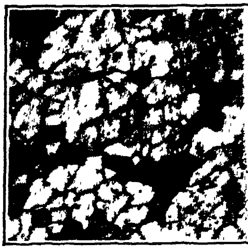
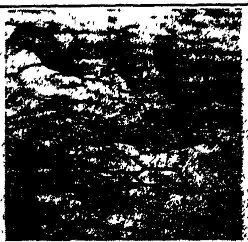
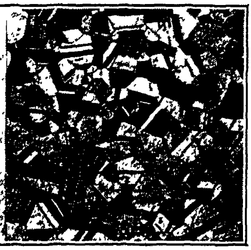
Admiralty brass is about the same as Cartridge brass except that it has about 1% tin: copper 70%, zinc 29%, tin 1%. The tin acts as a sort of hardener and it is necessary to anneal admiralty brass carefully before working it. It is considerably used for making condenser plates. Another alloy of this class is a little stronger. It is 62% copper; 37% zinc; 1% tin; 1% of tin as before, but lower copper content. This is often used in sheet metal work and in general foundry casting.

It has been stated above that there is considerable difference in the properties according to the condition of the alloy; that is, whether it is cast, cold-worked, or worked and annealed. A few photographs, reproduced by courtesy of the Bridgeport Brass Co., illustrate these differences. (See Figures 133 to 137.)

Three other illustrations from the same source show the effect of different amounts of cold rolling upon material originally heavily annealed. (See Figures 138 to 140.)

Class 2. Zinc-copper alloys, containing 35% to 45% zinc.

These brasses are not of the simple nature of the "alpha" brasses, but they contain a new constituent known as the "beta" solid solution. In general, these brasses contain a mixture of "alpha" and "beta" solid solution, or even fine "delta" solid solution under particular circumstances.

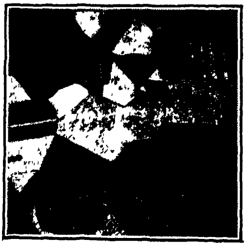
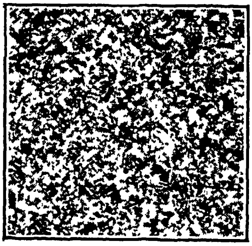
(Courtesy of Bridgeport Brass Co.)

Figure 133. Structure of Cast Alpha Brass

Figure 134. Structure of Cast Alpha Brass, Rolled

Figure 135. Structure of Alpha Brass Rolled; Lightly Annealed

Original magnification 75 times

(Courtesy of Bridgeport Brass Co.)

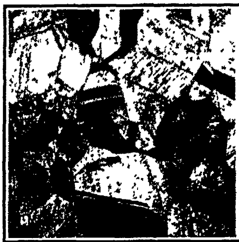
Figure 136. Structure of Alpha Brass Rolled; Heavy Anneal

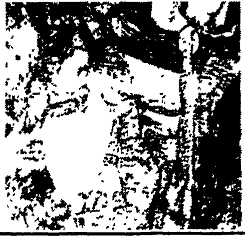
Figure 137. Structure of Alpha Brass Rolled; Annealed for Fine Grain

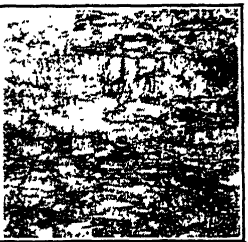
Original magnification 75 times

The alloys of this class are of great engineering importance. They have good mechanical properties and machine well.

In the cast condition they may be hot-rolled or extruded, and after hot-working, annealing, and quenching they become quite homogeneous "beta" constituent and will stand considerable cold drawing or rolling.







(Courtesy of Bridgeport Brass Co.)

Figure 138. Alpha Brass Rolled; Annealed; Re-rolled 20% Hard

Figure 139. Alpha Brass Rolled; Annealed; Re-rolled 40% Hard

Figure 140. Alpha Brass Rolled; Annealed; Re-rolled 70% Hard

Original magnification 75 times

Muntz metal, 60% copper, 40% zinc, is probably the best known of this type of brasses. The general practice is to keep the material as near to the standard proportions as possible. The mechanical properties of cast Muntz metal (see Figure 141) are about as follows:

Elastic limit	13,000 lb. per sq. in.
Ultimate stress	48,000 lb. per sq. in.
Elongation	55%
Red. area	52%
Brinell hardness	93

When this material is annealed at a temperature of about 600° C. or 1,120° F. it becomes very nearly homogeneous "beta" solid solution and if cooled quickly from this temperature or a little higher, it retains this type of structure. (See Figure 142.)

In this condition the material may be cold-rolled or cold-drawn and its mechanical properties somewhat improved.

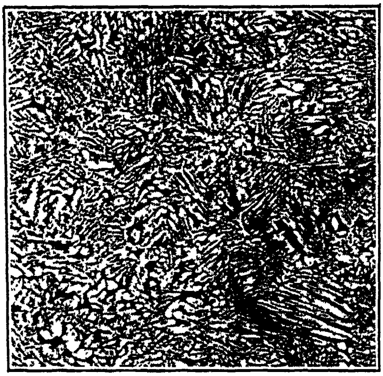
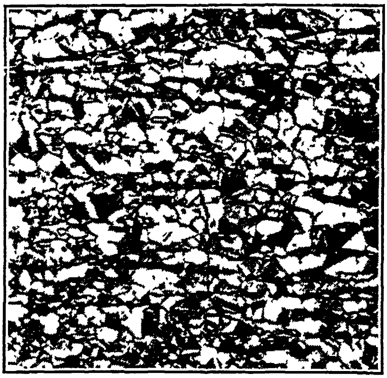


Figure 141. Structure of Cast Muntz Metal Beta Grains in Alpha Matrix

Original magnification 75 times



(Courtesy of Bridgeport Brass Co.

Figure 142. Structure of Muntz Metal Annealed Above 600° C. Cooled Quickly: Nearly Homogeneous Beta Solid Solution

Original magnification 75 times

Aitchison and Barclay give the properties of such material as follows:

	Hot-Rolled and Cold-Drawn	Extruded and Cold-Drawn	Extruded and Rolled
Elastic limit	13,000	27,800	18,400
Ultimate	29,600	43,200	55,200
Elongation	48.5%	31%	33.5%
Red. area	61		34.6
Brinell	116		116

Copper-Tin-Zinc Alloys.—The only valuable alloys of this series occur where copper is the controlling element. The strongest alloys are about 59% copper, 39% zinc, and 2% tin. The tensile strength of such an alloy is about 60,000 lb. per sq. in., but is too brittle to be of much value. The most valuable alloys of this class are much richer in copper, having an ultimate strength of from 35,000 to 40,000 lb. per sq. in. on an elongation of 20% to 30%.

The range of percentage is 75% to 85% copper, 17% to 5% zinc, and 8% to 10% tin.

Government bronze, or admiralty metal, known as 88-10-2, has 88% copper, 10% tin, and 2% zinc. When properly cast in sand molds the strength will approximate 30,000 to 35,000 lb. per. sq. in. The yield point is poorly defined, however, and the elongation is 14% to 16%. Much care in foundry practice is necessary or inferior material is sure to occur.

High Strength Brasses.—A number of zinc-copper alloys modified slightly by some other element, added for the purpose of producing superior mechanical properties, have been produced under various names. These alloys are known as high strength brasses or high tensile brasses, and among them are found such materials as manganese bronze, turbeston bronze, delta metal, etc.

The most common metals used in producing the "high tensile" brasses are iron, nickel, manganese, tin, aluminum, and occasionally vanadium.

Castings from these alloys, if properly made, will have tensile strength varying from 60,000 lb. per sq. in. to 100,000 lb. per sq. in., with a considerable degree of ductility. These brasses are generally approximately of the 60-40 type.

Delta metal, modified from the original patent of Alexander Dick, has the approximate composition as follows:

Copper	55%
Zinc	40%
Iron and manganese	4%
Other elements	1%

Manganese bronze, which is not a bronze but a brass, has a composition about as follows:

Copper	59·5 %
Zinc	39·0 %
Manganese	1.0 %
Aluminum	0.25%
Iron	0.25%

The last two elements named may be replaced by other metals and good results obtained.

The author has tested manganese brass which had a tensile strength of over 100,000 lb. per sq. in. and 15% to 20% elongation. Such material requires the best of raw materials and extreme care in foundry practice.

The mechanical properties of manganese brass as cast are about as follows:

Yield point	25,000–28,000 lb. per sq. in.
Ultimate strength	60,000–75,000 lb. per sq. in.
Elongation	35%–45%

No other metal or alloy possessing equal strength and toughness seems to be available for casting into intricate forms as successfully as can be done with this material.

Special Brasses.—There are many special brasses in both of the classes referred to above, but they are not of enough commercial importance, nor do they have sufficiently different physical properties, to warrant special discussion here.

Season Cracking.—Sometimes after articles manufactured from various brasses (and other metals, for that matter) have been put into service, spontaneous development of cracks is prone to occur. It seems to be established that these cracks are due to stresses left in the material after cold working. It has also been found that a light anneal which will not materially affect the mechanical properties of the material will relieve the stresses to such an extent that season cracking will not occur. A test has been devised which will indicate a tendency to season cracking. Immersion in a 1% solution of mercurous nitrate to which about 1% of nitric acid (sp. gr. 1.20) has been added, is sufficient to develop season cracks if they are liable to occur. Articles which pass this test are considered safe.

The Bronzes—Copper-Tin Alloys.—The useful alloys of copper and tin bear some points of resemblance to the alloys of the copper-zinc series, but there are also some notable differences.

In the first place the percentage of tin which can be added and still retain the "alpha" solid solution phase alone, is much less than is the case where zinc is concerned.

Examination of the part of the diagram of equilibrium which is shown in Figure 143 indicates at once that the limit for what is known as "alpha" bronze is about 12% of tin and the practical limit is about 10%.

Tin acts essentially as a hardener, but bronzes respond to heat treatment rather more than brasses. Certain special bronzes are of great use in resisting pressure and for bearing metals. Guillet draws the following conclusion from tests of heat-treated bronzes.

"1. That the alloys with 92% or more of copper are improved in maximum stress and elongation by quenching from temperatures between 400 and 600° C.

"2. That alloys with less than 92% copper are improved in strength and ductility by quenching from a temperature higher than 500° C.

"3. That the greatest strength is obtained from samples quenched from above 600° C. whatever the tin content of the alloy may be. The temperature which gives the best elongation depends upon the composition of the alloy.

"4. That the higher the tin content the more (in proportion) does the quenching operation improve the ductility.

"For the commercial alloys it is evident that a quenching temperature of between 600° and 800° C. may be profitable. The influence of tin on copper is very marked. In addition to a considerable hardening effect, the tin materially increases resistance to corrosion. Even in small quantities these benefits are felt and alloys containing only 2% or 3% of tin are often found in engineering practice."

Phosphor Bronze.—Phosphorus is often added to bronze to produce various desirable qualities. The alloys thus produced are of two classes.

Class 1. In which the percentage of phosphorus is very low and in which it acts as a deoxidizer or scavenger to produce a "clean" metal. Since the material made in this way contains only a trace of phosphorus, if any, it is doubtful if it should be called phosphor bronze.

Class 2. In which there is sufficient phosphorus to act as a definite constituent of the bronze, thereby making a ternary alloy. The ternary alloys are used for either cast or wrought material, but those alloys intended for casting usually contain more tin and phosphorus than those to be used in the wrought condition.

Aitchison and Barclay report a summary of the valuable properties of phosphor bronze, after Phillips, as follows:

"1. Its relative freedom from corrosion by salt water.

"2. Its high mechanical properties as compared with ordinary bronze.

"3. The fact that a spark cannot readily be obtained from it by a blow.

"4. The fact that phosphor bronze containing a high proportion of phosphorus has a low coefficient of friction in conjunction with most other metals, and is hard enough to resist abrasion satisfactorily

"The above properties indicate that pnosphor bronze is particularly suited for the manufacture of boiler fittings, for fittings exposed to sea water, for the construction of machinery used in the manufacture of explosives, and for use in bearings in high speed machinery."

Lead Bronzes.—Lead is often added to bronzes to be used for bearings for the purpose of increasing the plasticity of the matrix. The lead and tin contents are varied according to the demands of the service required. It is rather difficult to prevent segregation of lead in casting such bronzes and some element such as, for instance, nickel, is generally added to diminish this tendency.

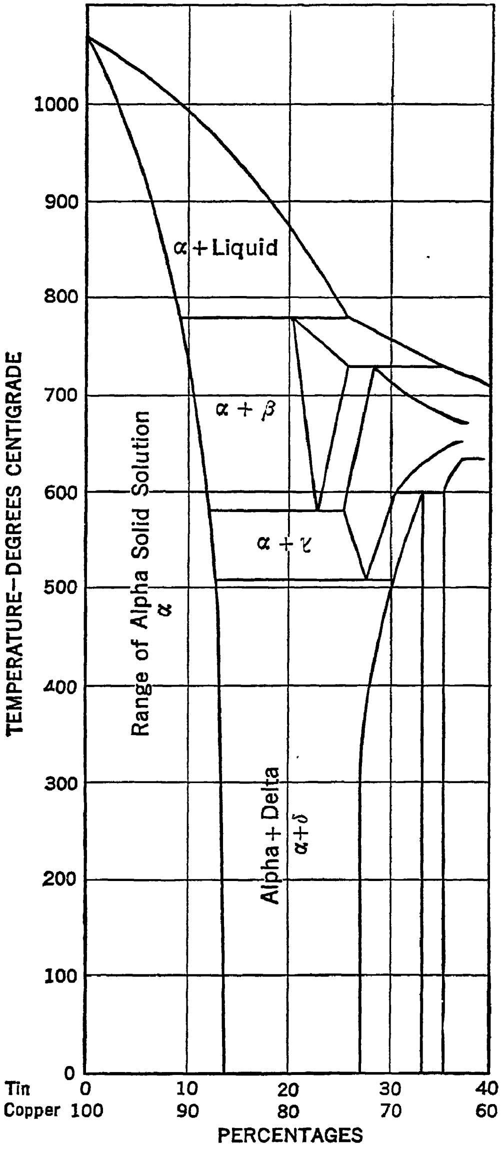


Figure 143. Equilibrium Diagram of Copper-Tin Alloys (From Rosenhain's Metallurgy)

Aluminum Bronze.—Aluminum bronze is not really a bronze but a copper base aluminum alloy; about 90% copper and 10% aluminum, with sometimes about 1% of iron. It is very strong, hard, and resistant to corrosion.

Silicon Bronze—Copper, Tin, and Silicon.—Silicon bronze is very similar to phosphor bronze except that phosphorus is detrimental to electrical conductivity while silicon is not.

Two very complete lists of commercial bronzes will be found by reference to Kent's Handbook. One table is for sand-cast copper base alloys and the other for wrought copper base alloys. The chemical composition is given, also the strength, ductility, and hardness. Brief remarks about the uses of each alloy are included.

Babbitt Bearing Metals: White Metal-Bearing Alloys.—These alloys are composed of tin, antimony, lead, copper, and some arsenic. Table 13 shows the extreme variability of composition.

Bearing Bronzes.—A great many tormulas for bearing bronzes are in existence but many of them are of doubtful value. The whole range of engineering work can be satisfactorily covered by a comparatively few of the best. Many factors enter into the suitability of an alloy for bearing purposes. An alloy that was suited for a high-carbon, nickel-chrome steel, heat-treated journal would probably ruin a journal of soft, low-carbon steel. Furthermore, the mere selection of the proper alloy for a particular service does not necessarily imply that the bearing will give satisfaction, for quality of workmanship, accuracy of fitting, and many other factors all enter to make or mar the result.

The harder bearing bronzes are phosphor bronzes, containing 0.25% phosphorus, and about 11% tin. The plasticity of the matrix is controlled by the variation of the lead content from about 0.25% to 2.5%. Sand casting, chill casting, or

TABLE 13. BABBITT METALS OR WHITE METAL ALLOYS

Alloy Grade Number	Composition Per Cent					Brinell Hardness		Melting Point Deg. F.
	Sn	Sb	Pb	Cu	As	At 70° F.	At 212° F.	
1	91	4½	0.35	4½	0.10	28.6	12.8	437.0
2	89	7½	0.35	3½	0.10	28.3	12.7	460.4
3	83⅓	8⅓	0.35	8⅓	0.10	34.4	15.7	462.2
4	75	12	10	3	0.15	29.6	12.8	365.0
5	65	15	18	2	0.15	29.6	11.8	365.0
6	20	15	63½	1½	0.15	24.3	11.1	365.0
7	10	15	75	0.50	0.20	24.1	11.7	464.0
8	5	15	80	0.50	0.20	20.9	10.3	469.4
9	5	10	85	0.50	0.20	19.5	8.6	469.4
10	2	15	83	0.50	0.20	17.0	8.9	473.2

1. Is suited for crank pin service in internal combustion engines. It must be well-confined or used as a thin layer sweated onto bronze because it is very plastic and liable to pound out; but it is the least liable of all to crack.

2. For much the same use as 1, but is less liable to pound out.

3. Is the hardest and has the highest bearing value. It is the original formula cf Isaac Babbitt.

4. Is excellent for main engine bearings and general machinery. It will stand severe punishment, but not high temperatures.

The lead base Babbitts stand higher temperatures than the tin base, but they are very soft and have low bearing values.

(For complete table see Proc. A S. T. M., p. 539, 1920.)

centrifugal casting also vary the properties of these alloys to a considerable extent.

The more plastic bearing bronzes have a lead content of from 10% to 15% and a little lower tin content than the harder class. These bronzes are dioxidized with phosphorus but there is scarcely a trace of it to be found in the alloy.

Alloys of Tin, Lead, and Bismuth.—By variations in the percentage of these metals, a series of alloys may be produced with melting points all the way from about 205° F. to 453° F. while alloys of tin, lead, bismuth, and cadmium give a series from about 150° F. to 203° F. Collectively these are known as *low melting point alloys.*

These alloys are valuable for use in sprinkler heads of automatic fire sprinkler systems. In these heads the cover is set with a compound link soldered together with one of these alloys. When the heat is too intense the metal melts and releases the cover. Links for fire door release, fusible plugs, etc., are also made from these alloys.

Lead-Tin Alloys.—Lead and tin alloy in all proportions, the most important series of alloys being those used as *plumbers' solder* which contains 33% to 50% of tin. "Half and half" is the ordinary commercial solder. The best solder for wiping joints in lead pipe is about 2 parts lead to 1 part tin. This alloy stays pasty through a considerable range of temperature. The best solders for electrical work are rather hard and carry about 2 parts tin to 1 of lead.

Nickel and Non-Ferrous Nickel Alloys.—Nickel occurs in various forms of ore, and the reduction processes give a rather variable product so that nickel is a flexible term when applied to the commercial product.

The usual nickel of commerce, except electrolytic nickel, is brittle, both hot and cold, but the purer forms may be made malleable by adding 1 lb. of magnesium to 1,000 lb. of the molten nickel before pouring into the molds. In this form the metal is malleable both hot and cold and can be rolled, drawn, or forged into any commercial shape.

Malleable nickel is available as forgings, cold-drawn rods, hot-rolled rods, cold and hot-rolled sheets, cold-rolled strip, seamless tubing, welded tubing, wire, and wire screen. It is used in apparatus for handling foods and chemicals and for resisting heat.

Alloys of Nickel and Copper.—Copper and nickel alloy in solid solution in all proportions and when treated with magnesium, as in the case of malleable nickel, are malleable both hot and cold throughout the entire range.

Effect of high temperature on the physical properties of nickel and its alloys. Nickel and high nickel alloys retain their strength and ductility to a surprising degree even under considerably elevated temperature. Ninety-nine per cent nickel with an elongation of 51% and a tensile strength of 81,000 lb. at 70° F. actually increases in strength and ductility up to 400° F., and at 1,400° F. still has a strength of about 30,000 lb. per sq. in., with no appreciable reduction in the ductility.

Monel Metal.—Monel metal is refined directly from the ore without changing the natural relations of nickel and copper. The smelting and refining merely remove the undesirable elements. It contains approximately 67% nickel, 28% copper, and 5% other metals.

In tensile properties it closely resembles steel. It is tough and ductile and can be machined, forged, soldered, brazed, and welded by the electric or oxyacetylene method. It lends itself admirably to casting, and many intricate patterns have been cast successfully. In its cast form it has the advantage of unusually high tensile strength.

In addition to its resistance to corrosive conditions, monel metal also resists oxidation, due to its high nickel content, since nickel possesses in a high degree the property of withstanding the oxidizing influence of hot gases.

On rolled rods the yield point varies from about 44,000 to 63,000 lb. per sq. in., and the ultimate strength from about 85,000 to 95,000 lb. per sq. in. The variation is about proportional to the mechanical reduction of section. The elongation would be about 40%. Castings show a yield point of about 37,000 lb. per sq. in., and an ultimate strength of about 72,000 lb. per sq. in. with an elongation of some 34%.

Typical uses of monel metal are valve seats, turbine blading, gas engine valves, filter screen cloth, pump rods, tie rods for chemical vats, dye house equipment, mining equipment, dairy and hotel kitchen equipment.

Electrical Resistance Alloys.—A large number of nickel alloys are used on account of their electrical properties, coupled with their resistance to oxidation at temperatures up to and including a red heat. Most of these alloys are corrosion-resistant as well, and may be used for this property or for their resistance to oxidation without regard to their electrical properties.

The most important are perhaps in the nickel-chromium group, many of which may be successfully used for heating elements, up to 2,000° F. They contain from 60% to 80% nickel, 10% to 20% chromium, and 0% to 25% iron with a trace of manganese in some varieties.

Besides these there are various ferro-nickel alloys, nickel-copper, and nickel-copper-zinc alloys.

Nickel silver or German silver is very variable in content, but is 50% to 70% copper, 5% to 30% nickel, and 14% to 40% zinc. The zinc is generally not over 30%.

These alloys are obtainable in regular brass mill shapes.

Die Casting Alloys.—Die casting alloys are classified under four groups.

Group A. *Zinc alloys*, consisting essentially of zinc alloyed with tin, copper, and aluminum. These are corroded by alkaline or saline solutions. They may be easily polished but tarnish quickly. They may be plated with nickel, copper, brass, silver, or gold. They are not strong. Used for calculating machine parts, vending machines, trimmings, etc.

Group B. *Tin alloys*, consisting essentially of tin alloyed with copper, lead and antimony. These are Babbitts used for various kinds of bearings.

Group C. *Lead alloys*, consisting essentially of lead alloyed with tin and antimony. Used for light-pressure bearings, casket trimmings, fire extinguisher parts, etc. They resist corrosion fairly well.

Group D. *Aluminum alloys*, consisting essentially of aluminum alloyed with copper. Used for automobile and aeroplane parts, magneto parts, vacuum cleaners, phonographs, milking machines, vending machines, etc.

Brass and bronze are difficult to die cast successfully.

Aluminum and Aluminum Alloys.—Aluminum and aluminum alloys have entered the commercial field on account of special characteristics which have made them more desirable than the materials which they have displaced. The most important properties of aluminum and aluminum alloys are low specific gravity and ease of fabrication into the forms in which they are used.

The property of specific lightness is retained in all the aluminum base alloys. No casting alloy of aluminum has a density more than 10% greater than that of the parent metal and some are actually lighter. The so-called "strong alloys" of aluminum which upon mechanical and heat treatment develop properties comparable with those of mild steel, have an increase of density of only slightly more than 3% at the maximum, and one of these alloys is also lighter than pure aluminum.

Commercially Pure Aluminum.—Although it is possible to obtain aluminum of high purity (99.983% aluminum), commercially pure aluminum may be considered as a natural alloy with a few tenths of 1% of accidental impurities. This metal shows a considerable improvement over the high purity material as regards tensile strength, yield point, and hardness. It is somewhat less ductile and somewhat less resistant to corrosion.

The physical properties of this metal, called 2S in accordance with the nomenclature of the principal domestic manufacturer, are shown below:

Tensile strength	12,000–16,000 lb. per sq in.
Yield point	4,000– 7,000 lb. per sq. in.
Elongation	30%–45% in a gauge length equal to four times the diameter of the test specimen.
Brinell hardness	10 mm. ball. 500 kg. load 22 to 27.

Variations of structure occasioned by cooling conditions in production of castings or by mechanical work and subsequent annealing, account for the wide range of values in the above table.

Commercially pure aluminum is practically never used without the addition of an alloying element in the manufacture of commercial castings, because of its relatively low strength and because of its difficult foundry characteristics, although a little is used in cases in which the electrical or chemical properties are essential.

As wrought metal, this material finds a wide commercial use; it is fabricated into sheet, plate, foil, bar, rod, wire, seamless tubing and pipe, molding and shapes both extruded and rolled, rivets, stampings, ingots of various forms, and special apparatus.

This wrought material is obtainable in various so-called "tempers." The temper is change in hardness caused by cold work which results in strain hardening. Some of the materials are only obtainable in the annealed state and some only in the lower "tempers."

The mechanical properties of commercially pure aluminum (2S) in the various tempers are shown as follows:

Temper	Tensile Strength lb. per sq. in.	Elongation % in quantities
Soft	12,000–16,000	35–40
¼ hard	14,000–18,000	5–10
½ hard	16,000–20,000	3–7
¾ hard	19,000–23,000	1–4
Hard	22,000–minimum	1–4

Sheets in either the ½ hard or the ¼ hard temper may be bent flat upon themselves in any direction without cracking. This is a more accurate indication of the ductility or "workability" of the metal than is the elongation.

Aluminum—Manganese Alloy.—This alloy, called 3S by the principal producer, contains 1¼% manganese. It is similar to the "commercially pure aluminum." Except for the so-called "strong alloys" which may have their physical properties improved considerably by heat treatment, it is the only alloy which is produced in this country in a wide variety of wrought forms. It may be obtained in practically all of the forms in which the commercially pure material is obtained. The mechanical properties of this alloy are noticeably improved, especially in the harder tempers, but the addition of the alloying element, manganese, does not decrease resistance to corrosion, as is often the case under such conditions.

The mechanical properties of aluminum—1.25% manganese alloy (3S)—are as follows:

Temper	Tensile Strength lb. per sq. in.	Elongation % in quantities
Soft	15,000–18,000	15–20
¼ hard	18,000–22,000	5–8
½ hard	20,000–24,000	2–6
¾ hard	24,000–29,000	1–4
Hard	27,000–minimum	1–4

Uses for Commercially Pure Aluminum and 1.25% Manganese Alloy (2S and 3S).—These materials are used for a multitude of purposes where a material of moderate strength and low specific gravity is desired and where cold forming at the same time is essential. In general the hardest temper which can be used without danger of cracking is desirable. Quite a wide range of mechanical properties is available on account of the various tempers of these two materials.

Both of these materials may be welded by use of the oxy-hydrogen blowtorch and the use of a suitable flux. Somewhat more skill is necessary in handling the 1.25% manganese alloy than in the case of the commercially pure alloy.

Strong Aluminum Alloys.—Besides the materials already considered there are a number of alloys which, when properly treated, possess quite superior mechanical properties. The two materials already described are wrought materials and the various "tempers" are produced by strain hardening, that is, cold working.

In the alloys of the strong alloy class, the materials are also wrought, but the working in these alloys is generally for the purpose of obliterating the cast structure of the material rather than to produce strain hardening. In consequence the working is often done while the material is hot, although cold working is used in sheet rolling, wire and tube drawing, etc. In contrast to the temper produced by strain hardening in the 2S and 3S alloys, the temper in the strong alloy is produced by heat treatment combined with sufficient working of the material.

Beside the temper of the heat treatment, a certain amount of strain hardening temper is possible, depending on the condition as determined by the heat treatment and the result desired.

Heat Treatment of Aluminum and Aluminum Alloys—Annealing.—In the case of commercially pure aluminum (2S) and the 1.25% manganese alloy (3S), the only heat treatment that amounts to anything is annealing to obliterate the effects of the strain hardening. To accomplish this in commercial practice the temperature is elevated to around 700° to 750° F. The higher temperature is required for the 3S alloy to insure complete softening. This annealing process consists of a recrystallization which is practically instantaneous as soon as the temperature is reached. However, as soon as the recrystallization has taken place, grain growth immediately sets in at a rate which is higher, the higher the temperature. As large grain size is undesirable because of inherent weakness of such structure, the temperature should not remain at very high temperatures for any considerable time.

Annealing of the "strong alloys" is carried out at a much lower temperature, that is, at about 650° F. This temperature must be adhered to as closely as possible since a lower temperature may not completely remove the strain hardening, and a higher temperature may result in a partial heat treatment unless the alloy is subsequently cooled very slowly through the annealing range.

Solution Heat Treatment and Precipitation Heat Treatment.—In the case of the strong alloys superior mechanical properties may be developed by proper heating and subsequent quenching and "aging."

In solution heat treatment the temperature of the material is considerably higher than that for annealing, and the material must be held at the proper temperature long enough to permit the solution of the soluble constituents. The time varies somewhat with the mass of the metal in the furnace, the dimensions, and with the amount of previous mechanical working. The variation is so great that for small masses, thin sections, etc., it may be as low as 15 minutes or less, whereas for heavy sections and large masses several hours of soaking may be necessary.

Accurate temperature control is essential. Too low temperature results in incomplete solution and inferior quality from this source, while too high a temperature results in partial melting or "burning." In general these temperatures range from 920° F. to 980° F., and after the proper time at these tempera-

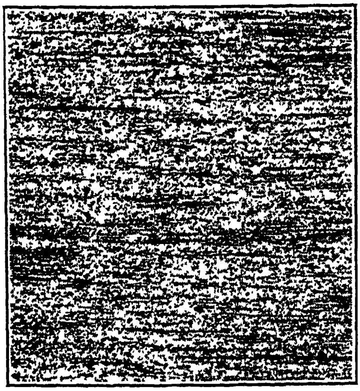
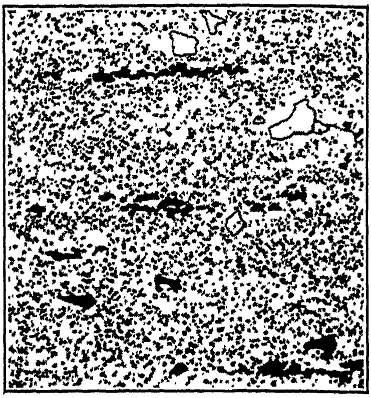


Figure 144. Structure of Strong Aluminum Alloy 17SH

Shows the microstructure of sheet which had 50% reduction by cold rolling. The cold working has broken up the original grains into fragments, and no definite grain boundaries can be seen.

Original magnification 100 times—etched with HF-HCl-HNO_3 mixture



(Courtesy of Aluminum Co. of America)

Figure 145. Structure of Strong Aluminum Alloy 17SH

Shows a portion of Figure 144 at higher magnification. The outlined large, white particles are $CuAl_2$, the black particles are Cu-Fe-Mn constituent, and the small particles in the matrix are precipitate of $CuAl_2$.

Original magnification 500 times—etched as in Figure 144

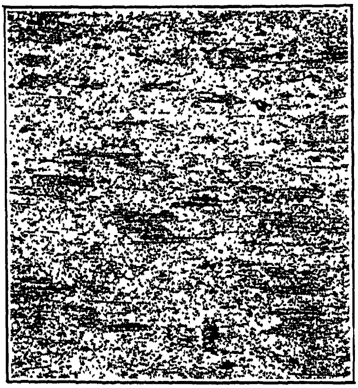
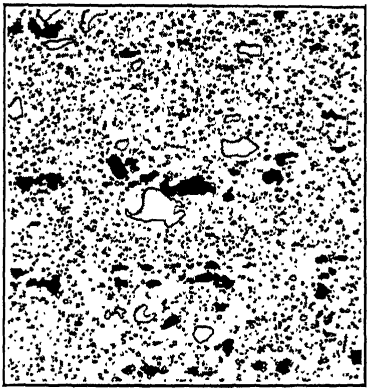


Figure 146. Structure of Strong Aluminum Alloy 17SO

Shows the microstructure resulting from annealing the material of Figure 144. The annealing caused recrystallization of the cold-worked metal and the boundaries of the newly formed grains are shown.

Original magnification 100 times—etched as above



(Courtesy of Aluminum Co. of America)

Figure 147. Structure of Strong Aluminum Alloy 17SO

Shows a portion of Figure 146 at higher magnification. The constituents are similar to those shown in Figure 144.

Original magnification 500 times—etched as above tures the material *must be quenched* in order that the dissolved constituents may be retained in solution. Full details of the exact temperature to be used may be had from the producers of this material.

"Aging" and Precipitation Heat Treatment.—After the solution heat treatment, a precipitation of some of the dissolved constituents is essential to the development of the best mechanical properties. Some of the alloys accomplish this precipitation spontaneously and more or less gradually after quenching. This spontaneous precipitation is called "aging."

Some of the alloys will not spontaneously change their characteristics, and a low temperature treatment at 250° F. to 320° F. is necessary to promote the precipitation. This is called precipitation heat treatment.

The time for the artificial aging or precipitation heat treatment varies from about 8 to 18 hours, depending on the temperature maintained.

Table 14. Normal Composition of Strong Aluminum Alloys

Alloy	Copper %	Manganese %	Magnesium %	Silicon %
17S and duralumin	4.0	0.5	0.5	
25S	4.5	0.8	0.0	0.8
51S			0.6	1.0
A 17S	2.5		0.3	
B 17S	3.5		0.3	
(Special) C 17S	4.0	0.6	0.5	1.25

Figures 144 to 149 show the micro-structure of wrought duralumin type alloys in the hard-rolled, annealed, and heat-treated conditions.

Table 15 shown on page 257 gives the strength of the alloys.

The capacity of these alloys to undergo cold-forming processes successfully is quite variable. The relative capacity of

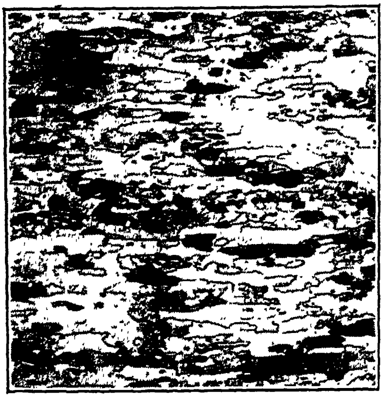
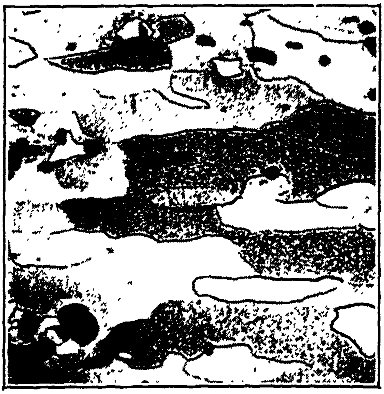


Figure 148. Structure of Strong Aluminum Alloy 17ST

Shows the microstructure which results when the metal shown in Figures 144 and 146 was heated to 900° to 950° F. and quenched. The alloy in this condition is essentially a solid solution of copper, magnesium, and silicon in aluminum. The various colors shown result from difference in orientation of the crystals making up the structure. The treatment in this instance resulted in the solution of all of the $CuAl_3$ precipitate shown in Figures 144 and 146.

Original magnification 100 times—etched as above

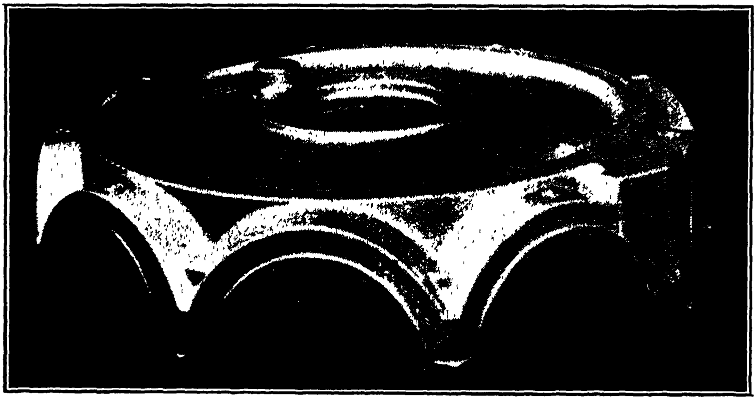


(Courtesy of Aluminum Co. of America)

Figure 149. Structure of Strong Aluminum Alloy 17ST

Shows a portion of Figure 148 at higher magnification. Shows the grain structure of the solid solution formed by heating and quenching. The small, light particles distinctly outlined are $CuAl_2$, which remained out of solution, while the small, black particles are the Cu-Fe-Mn constituent.

Original magnification 500 times—etched as above



(Courtesy of Aluminum Co. of America)

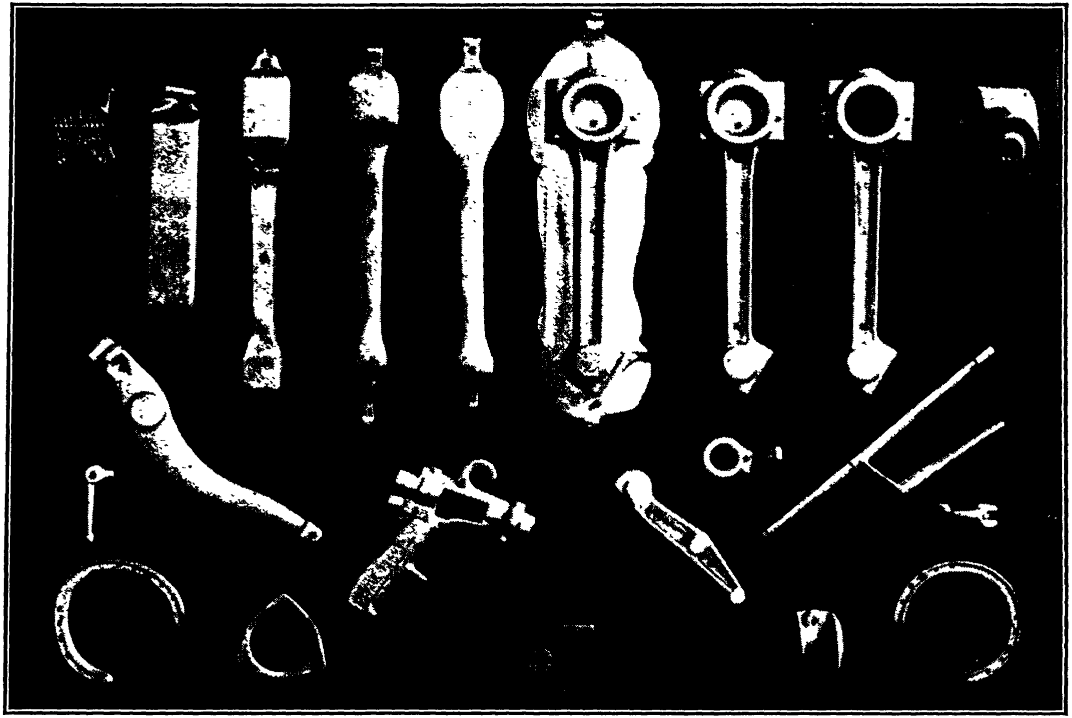
Figure 150. A Forged Aluminum Crankcase for Radial Airplane Motor. Alloy: Lynite 51ST. Weight: 28 lb.

TABLE 15. MECHANICAL PROPERTIES OF STRONG ALUMINUM ALLOYS

Alloy	Tensile Strength lb. per sq. in.	Yield Point lb. per sq. in.	Elongation % in 2 in.	Brinell Hardness 500 kg. load 10 mm. ball
51S O	14,000–19,000	4,000– 6,000	22–25	25– 32
51S W	30,000–40,000	15,000–20,000	20–50	55– 70
51S T	45,000–50,000	30,000–40,000	10–18	90–100
25S O	23,000–35,000	7,000–12,000	12–20	45– 55
25S W	45,000–53,000	15,000–30,000	15–22	65– 85
25S T	55,000–63,000	30,000–40,000	16–25	90–105
17S O	25,000–35,000	7,000–10,000	14–22	45– 55
17S T	55,000–63,000	30,000–40,000	18–25	90–105
B 17S O	20,000–25,000		20–28	30– 40
B 17S T	42,000–50,000	20,000–25,000	20–28	65– 85
A 17S O	20,000–25,000		20–28	20– 40
A 17S T	35,000–45,000	15,000–20,000	20–28	55– 75
C 17S O	25,000–35,000	7,000–10,000	12–20	42– 55
C 17S W	55,000–63,000	30,000–40,000	18–25	90–105
C 17S T	63,000–70,000	50,000–55,000	8–14	95–125

See Figures 150 and 151.

The letters O, W, and T after the number of the alloy indicate the heat treatment.
O is annealed. W is quenched. T is quenched and aged.



(Courtesy of Aluminum Co. of America)

Figure 151. Miscellaneous Aluminum Forgings in Lynite 25ST and Lynite 51ST Alloys

high strength alloys for forming operations in the order of increasing difficulty appears in Table 16.

Table 16. Relative Capacity for Forming of Strong Aluminum Alloys

1. 51S O + A 17S O
2. B 17S O
3. 25S O + 17S O
4. A 17S T
5. 51S W
6. B 17S T
7. (17S shortly after quenching)
8. 25S W
9. 17S T + C 17S W
10. 25S T
11. 51S T (difficult to form)
12. C 17S T (difficult to form)

The success of these forming operations is largely dependent upon the character of the forming operation, the type and design and condition of the tools, and upon the type of lubricant used.

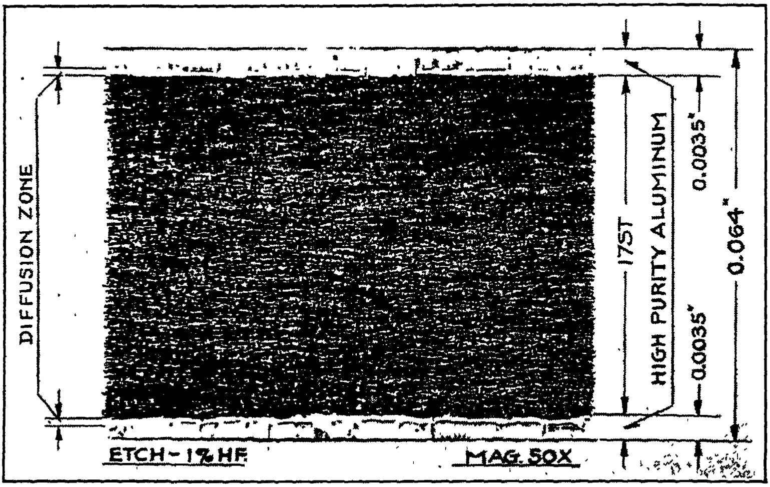
For machining operations the fully heat-treated or aged material seems to be the best. For forging, 25S and 51S are most easily worked, but all of the strong alloys respond well to ordinary hot-forming processes.

Alclad Sheets.—In certain cases where serious conditions exist, tending to produce excessive corrosion, the sheets of these aluminum alloys are not sufficiently resistant, so that a process has been developed in which a thin surface coating of high purity aluminum is produced in the ingot and rolled to produce a protective surface to the finished sheets or plates. This special sheet has made it possible to get great resistance to corrosion where long life is essential. (See Figure 152, a cross-section of an "alclad" aluminum sheet.)

Aluminum Casting Alloys.—Commercial castings of pure aluminum are not in extensive use on account of the relatively poor foundry characteristics and mechanical properties. However, by the addition of small percentages of certain other metals, marked improvements are obtained. Tensile strength, yield point, and hardness are increased. There is, however, a decrease in the ductility.

The alloying element may be considered as a sort of "hardener" and the amount to be used varies with the properties which it is desired to produce.

A great many casting alloys of aluminum have been developed, but the desire to retain as simple an alloy as possible in order to decrease the difficulties of composition control, has led to the general use of only a relatively few.



(Courtesy of Aluminum Co. of America)

Figure 152. Cross-Section of 14 Gauge Alclad 17ST Sheet

A corrosion-resistant strong aluminum alloy product, especially adapted for use in aircraft construction. It consists of a heat-treated aluminum alloy base protected by smooth, non-porous surface layers of corrosion-resistant, high purity aluminum of uniform thickness, alloyed and integral with the core. The high purity aluminum is electro-negative to the alloy and therefore exerts an electrolytic protection over exposed areas; as for example, the edges of sheets, channels, etc., and thus removes all apprehension as to the effect of deep scratches or abraded areas. Exhaustive corrosion tests show that this product is many times more resistant to ordinary corrosive agencies such as moist air and salt spray, than the unprotected strong aluminum alloys.

Original magnification 50 times—etched 1% HF

The elements which are used to any considerable extent in production of aluminum casting alloys are copper, silicon, zinc, magnesium, manganese, nickel, iron, and occasionally tin. Most of the commercial castings produced at the present time, are from alloys containing only copper or zinc, or both copper and zinc together with some silicon and iron. While aluminum-zinc alloys have been used considerably in Europe, the aluminum-copper alloys have found more favor in this country.

Aluminum-Copper Alloys.—Ordinary casting alloys of this type contain about 8% copper, or 7.5% with 1.5% zinc and 1.2% iron. In some cases a little silicon is added to the former of these in order to reduce the tendency of the castings to crack during the casting process. Even better results are obtained if both the silicon and iron are added in carefully controlled proportions.

These alloys machine well but are not pressure-tight. Where pressure-tightness is required, it is common practice to raise the copper content to about 11% to 14%. The tensile strength of these higher copper alloys is somewhat above that of the ordinary type, but the shock resistance is much lower. Recently silicon-aluminum alloys have been replacing these high copper alloys, since they have leak-proof characteristics, high tensile strength, and more ductility.

Aluminum-Zinc Alloys.—As has been stated, the aluminum-zinc alloys have not been used much in the United States. When properly cast they give good sharp castings, but seem to be sensitive to irregularities in the casting, and much skill is required to produce satisfactory results. Zinc is quite volatile and tends to distill out of the melt. Another shortcoming is their property of losing strength more rapidly at high temperature than do the common alloys of the metal.

Aluminum-Silicon Alloys.—These alloys normally are limited to a maximum of 11% silicon, but under special patented foundry methods it is possible to use up to 13% with good results. The iron content must be kept low in these alloys, or coarse grain will result with consequent brittleness. Silicon-aluminum alloys are very fluid; consequently intricate castings may be made even when there are heavy sections joined by thin webs. Castings of this material are quite free from leaks, and are resistant to corrosion. They can be machined readily and a considerable tonnage is manufactured.

One thing to be remembered in the use of this alloy is that the yield point is relatively low, and provision for this fact must be made in choosing it for any specific purpose.

Magnesium Alloys of Aluminum.—Magnesium alloys of aluminum have been and still are used to some extent. There have been some difficulties with foundry conditions, resulting in formation of dross and burning in the mold. It seems that these difficulties have been largely overcome, as is evidenced by the commercial production of high-grade castings from alloys in which magnesium is the major constituent.

Heat-Treated Castings.—Although the casting alloys described above are all intended for use without heat treatment, a few alloys have been developed which may have their mechanical properties much improved by heat-treating processes.

These alloys contain about 4% to 5% of copper and are modified by patented processes of heat treatment to produce superior properties. Important castings, where strength and light weight are imperative, are successfully made from this type of alloy. There are several processes of heat treatment designated by certain numbers, which are used in accordance with the properties desired.

Commercial Casting Alloys.—These alloys are used primarily for sand castings, although some of them are used for permanent mold castings or die castings. The range of properties is about the same for all types of casting, so that those in Table 17 for sand castings are typical. The strengths of test bars formed in metal molds are higher than these values, and where the casting can be designed to take advantage of this difference the permanent mold casting will show correspondingly high average properties, but this is not always possible.

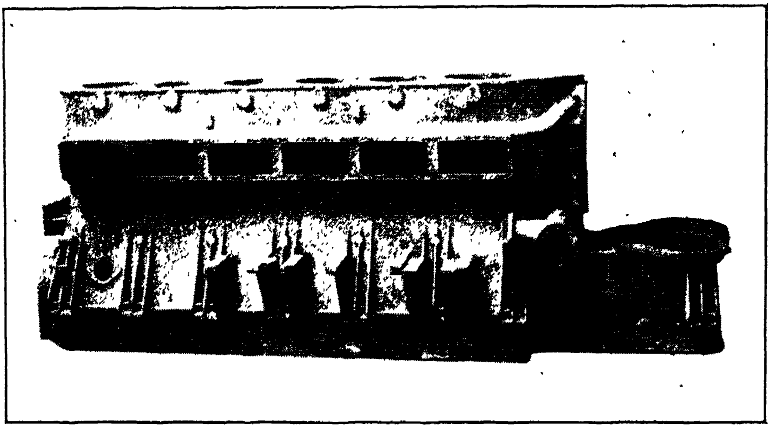
TABLE 17. PROPERTIES OF ALUMINUM SAND-CASTING ALLOYS

(From individually cast unmachined sand-cast test specimens)

Alloy	Approximate Composition	Ultimate Tensile Strength	Elongation % in 2 in.	Approximate Yield Point	Approximate Brinell Hardness
100	aluminum 99%	12,000–14,000	15–25	4,000	25
12	copper 8%	18,000–23,000	1– 3	10,000	65
112	copper 7.5% zinc 1.5% iron 1.2%	19,000–24,000	1– 2.5	11,000	60–65
109	copper 12%	20,000–28,000	0– 1.5	15,000	70
43	silicon 5%	17,000–22,000	3– 7	7,000	40
45	silicon 10%	17,000–21,000	1.5– 3	9,000	50
47	silicon 13% (modified)	24,000–31,000	5–15		
195	copper 4.0 HTT #4	28,000–38,000	6–12	13,500	65 (mm. 50)
195	copper 4.0 HTT #16	30,000–40,000	3– 8	21,000	75 (mm. 70)
195	copper 4.0 HTT #10	36,000–50,000	0– 5	27,000	100 (mm. 80)
196	copper 5. HTT	33,000–45,000	0– 2.5	27,000	110
145	zinc 10% copper 2.5% iron 1.2%	25,000–37,000	3– 6	12,000	65
122	copper 10% iron 1.2% magnesium 0.25% HTT 10%	35,000–40,000	0– 1	20,000	115
"Y" or 142	copper 4% nickel 2% magnesium 1.5% HTT	30,000–40,000	0– 2	25,000	100 mm.

A large cast aluminum crankcase for a dirigible motor is shown in Figure 153. The alloy is Lynite 194-5, and the weight of the casting is 732 lb.

Certain other alloys of aluminum are produced by foundries specializing in aluminum castings and claims of superiority made. It is probable that the composition of these alloys is essentially the same as one of those listed above and that any extra qualities are due to careful special foundry methods and heat treatments.



(Courtesy of Aluminum Co. of America)

Figure 153. Cast Aluminum Crankcase for Dirigible Motor. Alloy: Lynite 195-4. Weight: 732 lb.

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Proceedings of the A. S. T. M.

CHAPTER 9

CORROSION OF METALS

Loss from Corrosion.—As the use of metals in the industrial world has become more general the problem of corrosion has become more and more serious until at the present time the annual tax due to corrosion alone amounts to many millions of dollars, probably not less than $10,000,000 per year in the United States alone. Practical and scientific investigators have spent much thought, time, and money in the study of this problem, and several theories have been advanced to explain the causes and nature of corrosion in order better to attack the problem of corrosion prevention.

Lest misunderstanding should creep into the consideration of this matter, it should be stated at the outset that corrosion is ordinarily understood to refer to the attack and oxidation of metals and alloys by natural atmospheres and waters.

Several theories relative to the corrosion of metals, particularly iron, have been advanced, but they reduce in the last analysis to three main lines of thought which will be discussed briefly as a background to the subject.

The Acid Theory.—According to the acid theory the presence of an acid is necessary to dissolve the metal, after which oxygen changes the dissolved iron salt to rust. Even carbonic acid, formed by the solution of carbon dioxide in water was supposed to be sufficient to produce the effect of rusting of iron. Many experiments by careful investigators have tended to discredit this theory, and it seems to have been conclusively shown that the presence of *free* acid is *not* necessary for rusting.

The Hydrogen Peroxide Theory.—The hydrogen peroxide theory is based on experiments which showed that hydrogen peroxide is formed during the wet oxidation of metals. Water and oxygen are supposed to react with the iron to form ferrous oxide and hydrogen peroxide as the first stage, after which one-half of the peroxide is used up in oxidizing the ferrous oxide to form hydrated ferric oxide.

Many investigators have shown that hydrogen peroxide is not necessary to produce corrosion and that pure hydrogen peroxide does not oxidize iron, so that the theory seems entirely inadequate to explain the phenomenon at all satisfactorily.

The Electrochemical Theory.—According to the electrochemical theory, metallic substances tend to pass into solution in pure water; but a metallic substance will actually only dissolve when another substance having a lower "solution tension" is in contact with it and when there is sufficient electrolyte in the water to allow a current of electricity, however weak, to flow from the electropositive to the electronegative areas. This process was supposed to come to a stop as soon as corrosion conditions developed to polarize the cathodic portions of the surface. If, on the other hand, the water contained any oxygen or oxidizing depolarizer so that the cathodic portions were continuously depolarized, then the corrosion would proceed indefinitely.

Inadequacy of the Above Theories.—In regard to these theories, U. R. Evans writes as follows: "It cannot be said that either the acid theory, the hydrogen peroxide theory, or the earlier forms of the electrochemical theory offer much help to the practical users of metals. None of these theories explain the local and apparently capricious nature of corrosion. They fail to explain why sometimes corrosion produces in its early stages a compact and continuous layer, which brings the attack almost to a standstill, whilst at other times a porous flocculent corrosion product appears, which seems rather to stimulate the attack upon the underlying metal. They fail to elucidate satisfactorily the phenomenon of *pitting*, the type of corrosion which causes far more trouble to the engineer than any other type; none of the views suggested before 1916 explain why corrosion should proceed more quickly at the bottom of a deep pit than elsewhere, for such a place would be particularly inaccessible to oxygen and every other corrosive agent." Evans goes on to explain the immense amount of research work which has been done and then proceeds to the explanation of the newer electrochemical theory.

The Newer Electrochemical Theory.—Evans points out that J. Aston wrote a paper in 1916 in which he showed that the reason why wet rust promotes further rusting is not that it acts as a cathodic material, but that it acts like a diaphragm screening the underlying metal from the direct access of the oxygen. He says: "When two pieces of iron are immersed in the same liquid, and one is exposed to the action of dissolved oxygen and the other is shielded from it by means of wet rust, a current is set up, the shielded (rusty) electrode being the attacked pole or anode." Evans says that he was able to show that electric currents can be set up by "differential aeration" of many metals, including iron, zinc, cadmium, and lead, and he goes on to say: "We thus arrive at an explanation of the fact that corrosion is found to take place in an especially marked degree *at just those places to which oxygen has least direct access*." The older electrochemical theory of corrosion, which had directed attention mainly to the currents set up by the lack of uniformity in the materials, had given no explanation of pitting and intense local corrosion in areas shielded by porous *débris* or porous corrosion product." "This newer electrochemical theory, according to which the currents are set up mainly by the lack of uniformity in the distribution of oxygen, gives a rational explanation of these phenomena and will, it is hoped, prove of real use to the practical man."

It should be borne in mind that where metals of different potential are in contact, conditions as noted above may be greatly affected, and local couples caused by impurities no doubt aggravate conditions to a considerable extent.

Two Types of Corrosion Affecting Metals Immersed in Liquids.—Whether the current of electricity involved in the electrochemical corrosion process is externally applied or the result of local couples, does not materially affect the two main types of corrosion of metals immersed in liquids. These two types are known as: (1) the hydrogen evolution type, and (2) the oxygen diffusion type.

In the *hydrogen evolution* type of corrosion, the two metals involved at first exhibit a different potential within the electrolyte; hydrogen begins to appear on the more noble metal (cathode) and the less noble metal (anode) begins to pass into solution. If absorption of hydrogen by the cathode parts reduces the potential to a point where a potential balance is reached, then corrosion ceases, but if the bubbles of hydrogen begin to stream off before such a balance is reached, there is no further change of potential, and the corrosion process proceeds as long as there is sufficient active agent present. This action is fairly well recognized as regards the action of acids, but some of the metals at the negative end of the "potential series" will liberate hydrogen from neutral or even alkaline solutions.

The *oxygen diffusion* type of corrosion is by far the more common type in the case of the ordinary metals immersed in industrial waters.

The concentration of free acid in ordinary industrial waters is far too low to produce the hydrogen evolution type of corrosion and therefore a state of equilibrium is reached before the hydrogen begins to stream from the cathode areas. However, dissolved oxygen has the power of removing this hydrogen and therefore of depolarizing the cathode so that the process may proceed and the rate of corrosion may proceed as fast as the diffusion of oxygen will permit. Evans says, that direct chemical union with the oxygen *may* take place, but it is unlikely, at low temperature to lead to deep-seated change, since the oxide film, if formed uniformly over the whole surface, will tend to protect the metal from further attack.

From a practical standpoint it would seem then that corrosion may be caused by:

1. Direct chemical action.
2. Electrochemical process involving the liberation of hydrogen and not requiring the presence of dissolved oxygen.
3. Electrochemical process where hydrogen is not liberated but which requires the presence of dissolved oxygen in the liquid.
   (a) In the case of two different metals in contact, or in the heterogeneous metals.
   (b) In the same metal when there is unequal access of oxygen, in which case the parts most easily accessible become ennobled (cathodic).

Corrosion of Partially Submerged Metals Just below the Water Line.—When a metal is partially submerged the material directly under the surface is in contact with water more highly charged with oxygen than that a little deeper down. According to the principles as stated above, the metal in contact with the water of higher oxygen concentration becomes ennobled with respect to the parts in contact with water of lesser oxygen concentration. An electrochemical action is at once set up, resulting in attack a little below the surface.

Corrosion of Totally Submerged Metals.—Totally submerged metal in ordinary industrial waters may become corroded by galvanic action with oxygen when in contact with some other metal. Steel sheets of vessels in contact with brass bushings in service in salt water and left unprotected have become seriously corroded in a very short time; bronze propellers on steel shafts have often caused rapid corrosion to take place. But metals totally submerged not in contact with any other metal also become badly corroded, and this may be ascribed to unequal diffusion of oxygen; to collection of débris in spots which are thereby partially protected from oxygen and which thereby become cathodic, so that corrosion proceeds; or there may be segregation of impurities which will help to start the process. Once the process has started, inequalities in the density of the partially protective covering will cause the corrosion to proceed.

Pitting.—The localized form of corrosion, known as pitting, so prevalent in boiler tubes, pipes, drums, etc., appears to be caused by particles of débris which become lodged, and partially protect the surface, so that corrosion commences under the protected spot. The porous corrosion product continues to give partial protection, and so corrosion proceeds in the most protected spots, namely, at the bottoms of the pits, until perforation occurs. Of course, if surfaces are kept free from débris, such conditions will not start, and better still, if the water has been de-aerated or de-oxygenated the process will not proceed.

Erosion and Corrosion in Rapidly Moving Water.—Several cases of peculiar destruction of metals subject to the action of rapidly moving water have led to considerable speculation and experiment as to the probable cause. The most notable cases of this phenomenon were first noticed on the propellers of turbine-driven destroyers of the British Navy. Later, the same thing was noticed on the propellers of the *Mauretania* and *Lusitania* and some other "liners." Many theories were brought out and the cause was assigned to poor material, segregation, oxidation of metal by air drawn from the water by "cavitation" or the formation of vortex cavities, erosion by the water on the high-speed propellers, and electrolytic action between overstrained and normally strained metal.

Silberrad, in the *Journal of Society of Chemical Industries*, came to the conclusion that the deterioration is due to mechanical causes and the Board of Investigation and Research came to similar conclusions. They maintain that the cause is mainly erosion caused by hammer action due to the collapse of vortex bubbles, but there seems to be strong evidence that corrosion due to the effect of electric potential in the differently strained areas has some bearing on the subject, because reducing the power per wheel and thickening the material to reduce the stress has been reported to have resulted in a cure of the conditions. Others maintain that the reason for the cure is that the added metal has changed the contour and prevented the formation of vortex cavities.

Hydraulic turbine runners have suffered from this same phenomenon. Here the trouble developed from the back face of the blades, and not in the power face as in the case of propellers. "Cavitation" has been assigned as the cause, and change in speed or bucket contour is the cure in the case of medium-speed runners; and a low setting to practically eliminate the draft head is the cure in the case of high-speed runners.

Atmospheric Corrosion.—In his work on corrosion, Evans divides atmospheric attack on metals into two classes.

(1) "Tarnishing, which is defined as a thin, adherent film interfering with the original luster, and generally a change in color, often adding perceptibly to the weight."

(2) "Corrosion, which is the actual eating away of the material yielding a non-adherent product, which when removed generally causes a loss in weight."

Effect of Moisture and Polluting Gases.—It is very doubtful if dry unpolluted air will cause even tarnish to any appreciable extent on ordinary metallic articles, and it is also doubtful if the mere presence of moisture in the atmosphere in itself makes any appreciable difference.

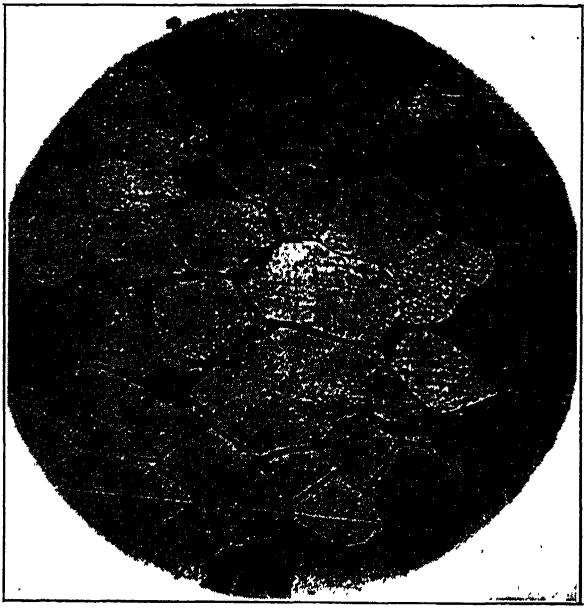
However, in climates where there are considerable quick differences in the atmospheric temperature, and resultant precipitation of dew, rusting of iron and steel will proceed very quickly. Once the rust spots are formed they form a protection which inhibits further corrosion.

It is a matter of common experience that atmosphere laden with polluting gases is capable of producing much more rapid corrosion than pure, unpolluted atmosphere. Sulphurous gases from power stations, acids, and various chemical fumes are active in increasing atmospheric attack upon exposed metal. Salt spray from the ocean and dust-laden air from various causes may also increase the corrosion quality of the atmosphere to a large extent.

Pitting of High-Speed Gear Teeth.—It has been found that a peculiar type of corrosion of the teeth of high-speed power gears has sometimes occurred to a dangerous degree and it is interesting to know that such action has been stopped by the introduction of an inert gas into the gear case. It has been reported that one engineer stopped the action by simply burning a candle in the chamber through which the air drawn into the case was passing.

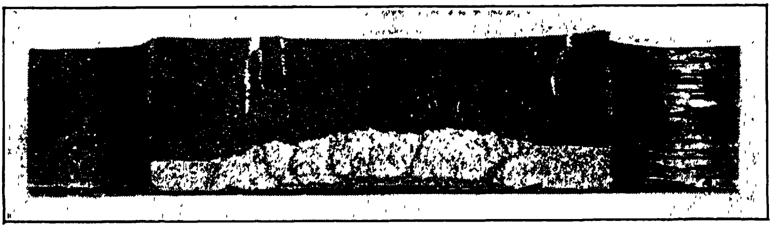
Caustic Embrittlement.—Another type of failure has been noted, particularly in the case of ruptured boiler shells. In this type of fracture a material normally very ductile and tough, breaks with a coarse, crystalline fracture showing extreme brittleness. The reason for this type of fracture has been traced to conditions of high localized stress combined with a high concentration of caustic in the water which comes in contact with the metal at the affected locality. This condition has been investigated by Straub and has been called "caustic embrittlement."

Figure 154 shows how the caustic produces a chemical effect on the grain boundaries of the metal at the critical location, thereby weakening them and finally causing the characteristic coarsely crystalline type of fracture as shown in Figure 155.



(Courtesy of F. G. Straub)

Figure 154. "Embrittlement Crack"
Original magnification 500 times



(Courtesy of F. G. Straub)

Figure 155. "Embrittlement Crack." Light portion is a fresh crack caused by the splitting of the plate

Relative Rate of Corrosion Due to Impurities.—The effect of impurities upon corrosion is dependent on so many factors that no simple statements may be made. Impurities in the metal may or may not increase tendency to corrosion. For instance, the presence of free graphite in iron promotes corrosion by non-oxidizing acids and lessens corrosion by oxidizing acids which are able to produce passivity. Again the form of the impurity, whether dissolved, or finely or coarsely divided, has a marked effect on its influence. Heat treatment of various of the metals changes the susceptibility to corrosion in many cases.

Wrought iron has often been cited as a superior metal to resist corrosion and numerous examples have been noted. Some of the articles which have been shown to have long life have been located in dry, even-temperatured climates where the air is of extremely high purity, but, when removed to different locations where bad conditions exist, corrosion has proceeded rapidly. Other wrought iron articles made many years ago by laborious hand processes have seemed to show remarkable resistance. It is supposed that the immense amount of localized working and densifying of the surface by the older processes has been largely responsible for this condition. Samples of high-grade iron made by modern processes have apparently not shown noteworthy superiority over some of the purer forms of iron. Manufacturers of wrought iron still claim superiority for their product.

In general, increase in the carbon content of steel up to the eutectoid percentage, i. e., 86% to 90% increases the tendency to corrosion. Various elements existing as alloying ingredients in steels appear to protect under some conditions and to have an unfavorable effect in others.

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CHAPTER 10

TEMPERATURE EFFECTS ON METALS

Physical Characteristics at Elevated or Subnormal Temperatures.—As advances in engineering practice call for design of apparatus at temperatures above or below normal, and as the stress conditions become more difficult to meet, it becomes increasingly necessary to determine the physical characteristics of materials at such temperatures.

Many materials suitable at normal temperature will be found unfit at some elevated temperature or temperature below the normal.

When Watt built his steam engine a pressure of 10 lb. per sq. in. was considered excessively high, but since that time pressures have risen to 50, 100, 150, 200, 250, 300, 350, 600, 700, and even 1,200 lb. per sq. in., with corresponding temperature increases, so that, with conditions of superheat, temperatures of 750° F. are met with.

Retort drums for use in the petroleum "cracking" industry for the production of gasolene require very high temperatures up to 1,000° F., although with not too excessive pressure.

Internal combustion engine parts, blowers for hot gases, and many other things are subject to high temperatures and stress at the same time. Life and property depend upon the reliability of the materials used in construction of such equipment.

At the other extreme are the excessively low temperatures, such as are encountered in refrigerating machinery and equipment, and particularly in aeronautical work, at high altitudes where very low temperatures with highly stressed material occur simultaneously. In this latter case particularly, the hazard is very great, and materials must be selected with the greatest care in order to meet the service which they must render.

Effects of Temperature on Iron and Steel.—The record of the Government "Tests of Metals" shows exhaustive tests of the effect of temperatures ranging from about 0° F. to about 1,600° F. Other investigators since have made similar tests and obtained similar results. Some investigators have carried on the work at low temperatures and so supplemented the work of previous investigators.

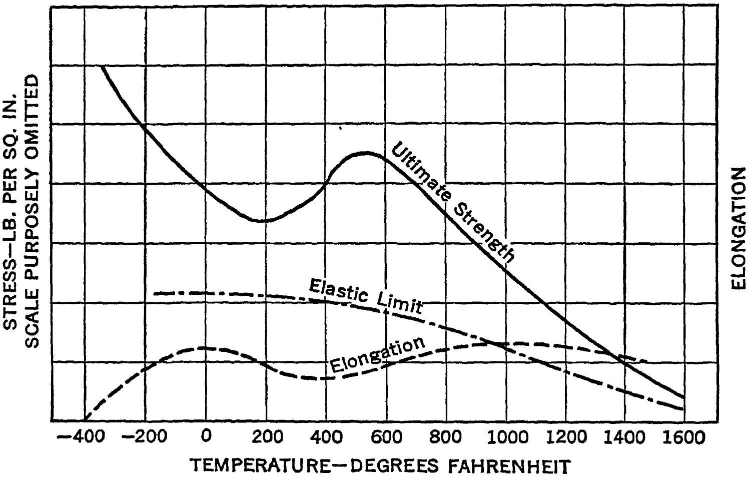

Figure 156. General Effect of Temperature on Plain Carbon Steels

In general the effect on hot-worked carbon steel and iron in tension is about as follows:

1. *Ultimate strength of carbon steels.* (See Figure 156.) On raising temperatures above 0° F. the strength decreases somewhat until a temperature a little above that of boiling water is reached. It then increases until a maximum is reached at about 550° to 600° F. Thereafter it decreases until at about 1,600° there is practically no strength left. As the

temperature is lowered below zero the strength rises rather rapidly, but the material becomes brittle.

2. *Elastic limit.* The elastic limit remains practically unchanged until the temperature reaches about 250° F., when it begins to fall off, falling off more rapidly as the temperature increases, but not as rapidly as does the ultimate strength after the 600° F. maximum has been passed.

3. *The modulus of elasticity* decreases about in proportion to the drop in elastic limit.

4. *The ductility* reaches one maximum at about normal atmospheric temperature, then decreases to a minimum; increases to another maximum at about 1,000° or 1,100° F., after which it decreases again. Again as the temperature falls below 0° F. the ductility is decreased considerably. It is probable that it is not safe to load steel for any length of time above the temperatures indicated by the high temperature maximum of elongations, that is, about 1,100° or 1,200° F.

High carbon steels are much more responsive to temperature changes than are low carbon steels.

Cast steels show effects similar to those noticed in the wrought materials.

Malleable cast iron is shown to have the same characteristics, although not as pronounced.

Ordinary cast iron shows hardly any effect, except the phenomenon of "growth" or expansion, which is permanent, for it does not contract to its original size on cooling.

Many alloy steels show somewhat the same characteristics as the carbon steels, but some, particularly chromium steels, have their maximum strength at normal temperatures and fall off in strength continuously, as the temperature rises.

Torsional resistance and crushing resistance at various temperatures vary in a way entirely consistent with the strength and ductility relations observed in the tension relations already discussed.

Impact Resistance.—Considerable work on the effect of temperature on impact resistance has been done by Reinhold, Charpy, Guillet, Langenberg, and others. Most of this work is summarized in Volume 24 of the Proceedings of the American Society for Testing Materials. Figures 157 and 158 are taken from the results as published in this summary. Figure 157 shows the results obtained on carbon steel bars. It indicates a maximum resistance at from 150° to 400° F. depending on the carbon content, then it shows a minimum at 800° to 1,000° F., and then a sudden rise to another maximum.

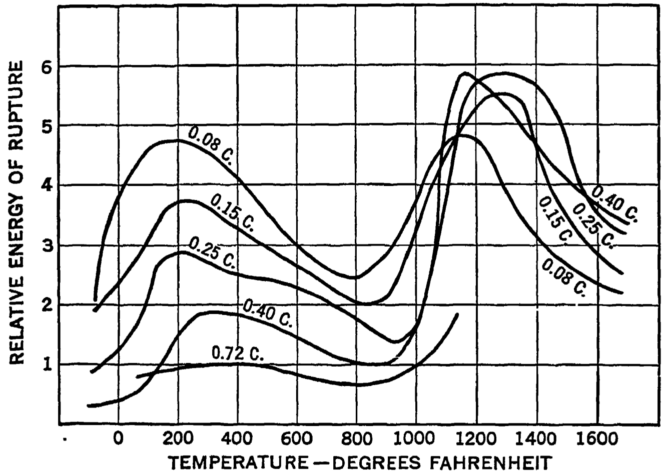

Figure 157. Results of Notched Bar Impact Tests of Carbon Steels

The first maximum is important when it is considered from a design point of view, because it falls within the temperature range where the material still has considerable rigidity and resistance to flow under slow stress. It indicates that machine parts would not fracture easily under impact and would not flow or distort.

The minimum values at about 800° to 1,000° do not correspond to the low ductility point at blue heat mentioned in connection with tension tests.

The second maximum is of interest in forging operations, but structurally these materials would be far too soft and plastic to stand any prolonged static load.

Another important point which should not be overlooked is the steep slope of the curve at ordinary atmospheric temperatures indicated by marked differences in impact resistance, within the temperature range at which a large majority of elements must perform their service.

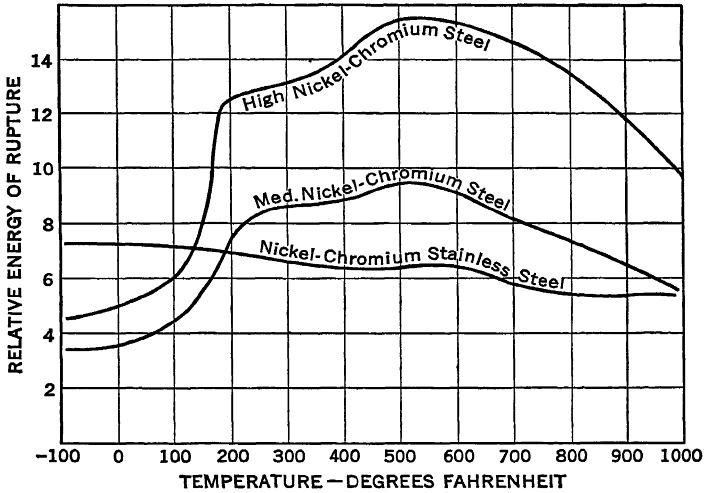

Figure 158. Results of Notched Bar Impact Tests of Nickel-Chromium Steels

Figure 158 for Ni Cr steels indicates not only the great variation in strength in some of the alloy steels but the fact that some have very little variation. Chemical and physical composition, heat treatment, and previous mechanical treatment, are apparently responsible for the great variations which have been observed.

Many of the alloy steels show a steady decrease in impact resistance as the temperature rises. The temperature effects on one steel are no criterion of the effects on some other.

Non-Ferrous Metals.—The strength of non-ferrous metals is lowered as the temperature above 70° F. is raised, in practically every case which has been reported.

Copper, tin, bronzes, and *aluminum bronzes* do not decrease in strength very much until 400° F. but thereafter the decrease is quite rapid.

Brasses and *monel metal* show a decline at once as the temperature is raised above 70° F.

Above 600° F. the ductility of the copper, tin, and copper-zinc alloys is practically gone, but monel metal has a wonderful combination of strength and ductility at all temperatures up to a red heat. Monel metal is largely used for high temperature work where strength and toughness are desired, especially where a non-corrodible material is essential.

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CHAPTER 11

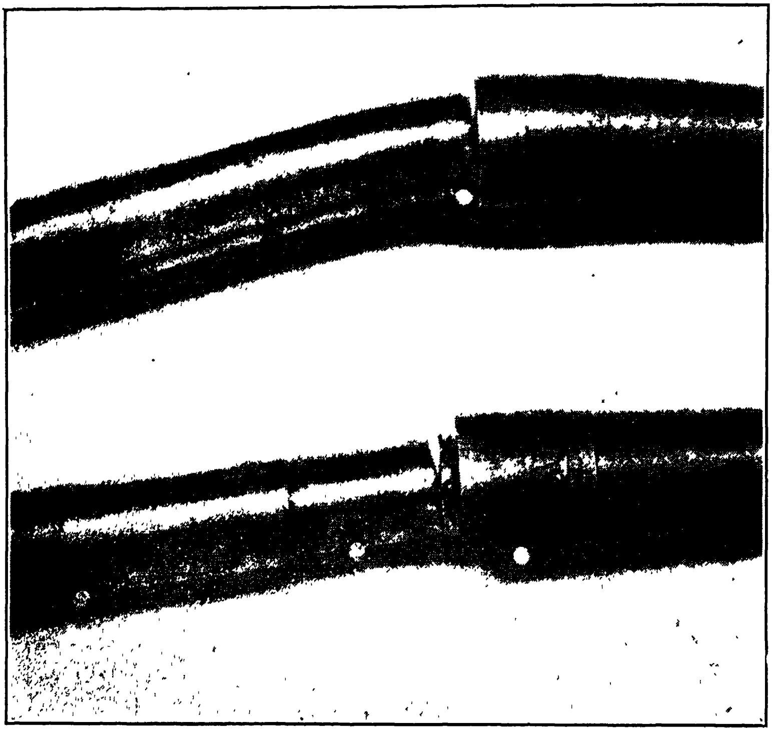
FAILURE OF MATERIAL UNDER REPEATED STRESS

Fatigue of Materials.—Until within a comparatively few years most attention had been given to the effect of static or steady stresses, with some allowances in certain cases for suddenly applied loads. Progress in mechanical development has introduced design requiring not only very high, but very variable stresses. Materials which would stand up indefinitely under static stress were found to fail in a peculiar manner when subjected to repeated stress or "vibration" as it was, and is, often called.

The kind of stresses which are involved may be either direct (tension or compression), or shearing (simple or torsional), or both. They may vary from a minimum to a maximum in the same direction or from a stress in one direction to one in the opposite direction. Variations of the former kind are called *simple repeated stresses.* The latter are known as *reversed repeated stresses,* and when the negative and positive values of the reversed stresses are equal, the term *alternating* stresses is used. *Range of stress* means the algebraic difference between the maximum and minimum values of stress, considering a reversed stress as negative.

Endurance is understood to mean the capacity of a metal to withstand repeated stress. The endurance limit signifies the highest unit stress which may be applied to a given material without producing rupture.

Fatigue is the term used to signify the phenomenon of breakdown and fracture under repeated stress. The characteristic fracture which occurs as a result of repeated stress beyond the endurance limit is generally referred to as a "fatigue fracture." Moore and Kommers show in their book that the term "progressive failure" is really more accurately descriptive. (See Figures 159 and 160.)

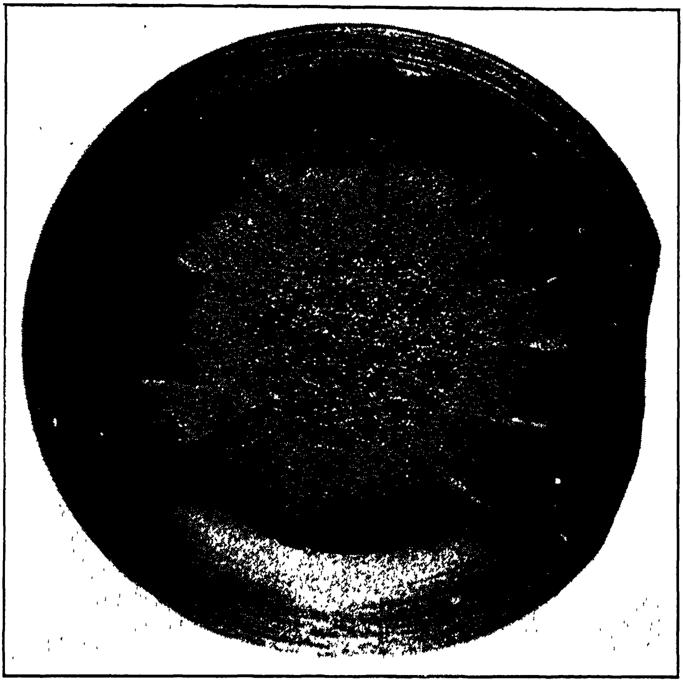


(Courtesy of H. F. Moore)

Figure 159. Static Failure and Fatigue Failure of Axle

The upper specimen failed under a single loading steadily applied, while the lower specimen failed under a large number of reversals of flexural stress. Note the sharp break in the lower specimen as contrasted with the gradual curve of the upper.

"Crystallization" Fallacy.—When metals are fractured as a result of repeated stress, they present quite a different appearance from that presented from failure by static stress. It used to be the common assumption that the material had "crystallized" due to the action of the repeated stresses, but this explanation was merely conjecture and has been shown by the results of many experiments to be quite incorrect. (See Figure 161.) Metals are inherently crystalline and there is no change in this characteristic due to repeated stress. Defective chemical composition, overheating, or harsh treatment in fabrication processes may often produce coarsely crystalline structure. These defects are apt to make such steels particularly weak in resisting repeated stresses. It should be emphasized that the coarse structure existed before the repeated stress was applied,



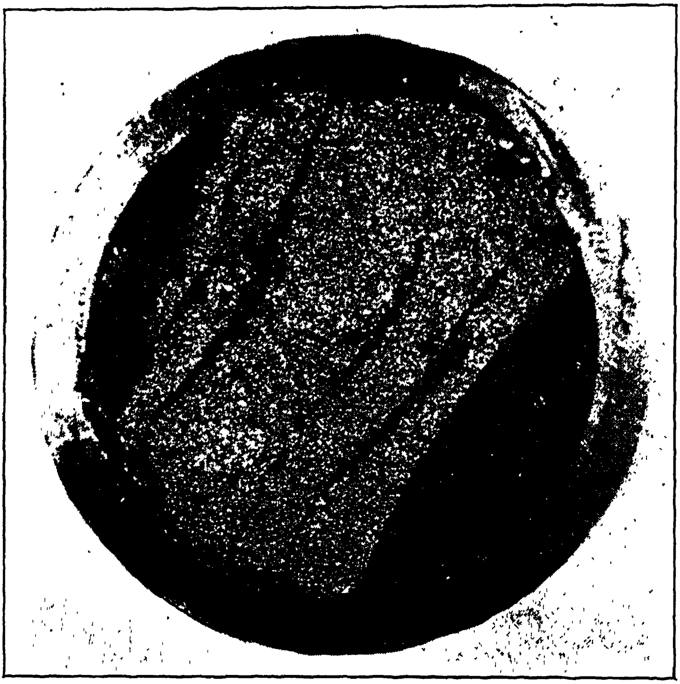
(Courtesy of H. F. Moore)

Figure 160. Fatigue Fracture of an Axle

This specimen failed after many thousands of cycles of reversed flexure. Note that the crack started around the circumference and gradually spread inward. As it spread, the walls of the crack battered each other smooth. Finally there was left only a small circle of sound metal. This could not stand even one cycle of reversed flexure and failed suddenly leaving a jagged, "crystalline" surface in the middle.

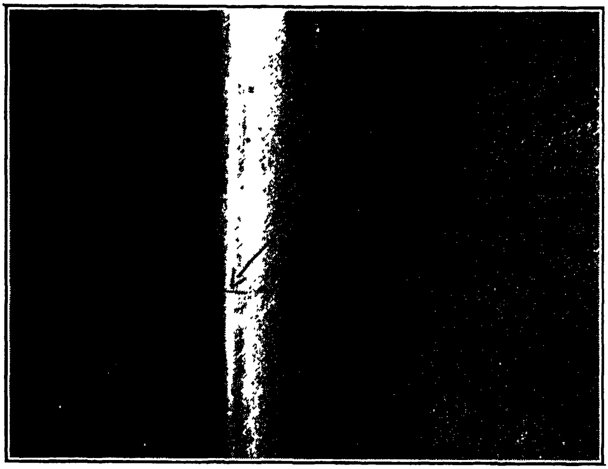
and did not change to that condition because of the repeated stress.

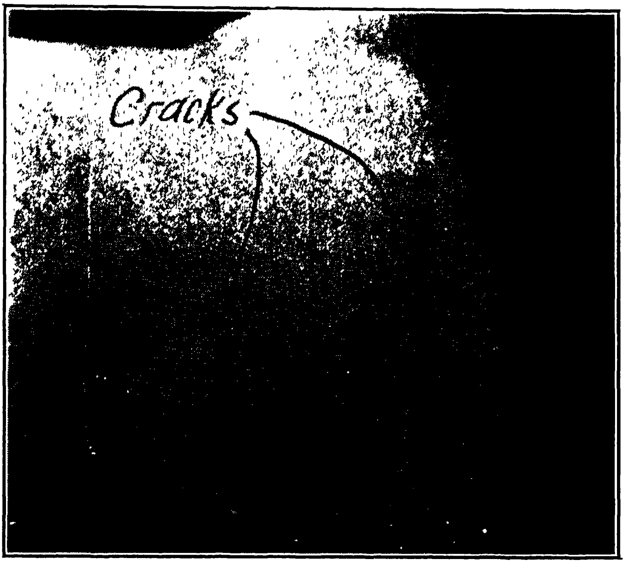
Another thing which has led to the erroneous idea of crystallization due to fatigue is that the mechanism of fracture in repeated stress is quite different from that in static failure, at least in materials with appreciable ductility. In static tests there is considerable flow of metal, reaching a maximum near the fracture; the grains become very much distorted, and the more or less distorted grains finally break to show a "silky" sort of fracture. In repeated stress there is no such general flow of metal, the mechanism is extremely local and starts at some crevice, flaw, or inclusion of an impurity (Figure 161),



(Courtesy of H. F. Moore)

Figure 161. Fatigue Fracture of Rod at Root of Thread





(Courtesy of H. F. Moore)

Figure 162. Fatigue Cracks in Machine Parts

Above: Fatigue crack in steam turbine blade. Crack has spread about half way across the blade.

Below: Fatigue crack in axle. Crack is made visible by rubbing surface of axle with kerosene, wiping clean, coating with a wash of whiting, and after whiting has dried, rapping axle and turning it around. If any fine cracks have formed, the kerosene will penetrate them and will be forced out by the rapping, discoloring the whiting.

and proceeds without regard of grain boundaries, from weak spot to weak spot until fracture finally occurs. It is this peculiar type of fracture which has led to erroneous conclusions as to the reason for its existence. (See Figures 163 to 165.)

Microscopic Indication of Incipient Failure.—In ordinary tension or compression testing it is well known that, up to the elastic limit, no permanent effect upon the characteristics of the grain structure occurs, but above the elastic limit a distortion of the grains becomes more or less general throughout the overstrained area. This distortion is of the nature of a slip on parallel planes of certain of the grains of the structure. These lines are quite apparent in the photograph of cold-worked alpha brass. (See Figures 138 and 139.)

When the plastic flow has proceeded to such a limited amount and no more flow is possible, fracture occurs at the weakest section. In the case of repeated stress, however, there is no such general distortion and reduction of area of cross-section, but rather an extremely local granular distortion occurs, due, doubtless, to some high local stress upon a few crystals near some impurity or irregularity of section. As this local granular disturbance proceeds, the grains so disturbed show an indication of internal slip finally resulting in the beginning of a minute, submicroscopic crack. This crack, which supposedly starts from some flaw or inclusion or irregularity in the structure, proceeds upon further repetition of the stress, until the cross-section is so reduced that further resistance is impossible and fracture follows. Every fracture of this nature shows two distinct parts; one which is more or less dull and wavy and shows the effect of rubbing and pounding during the slow development; the other a crystalline, clean fracture which occurred suddenly at the end. (See Figures 160 and 161.)

Effect of Localization of Stress on Endurance Limit.—The effect of localization of stress in structural elements may have a much more serious effect upon the endurance limit than

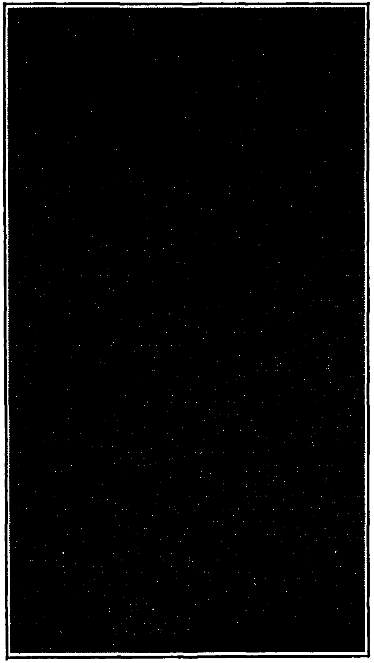


Figure 163. Fatigue Crack in Armco Iron

Original magnification 100 times—unetched

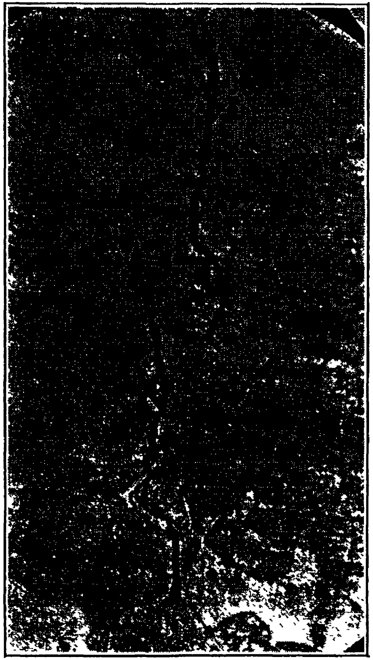
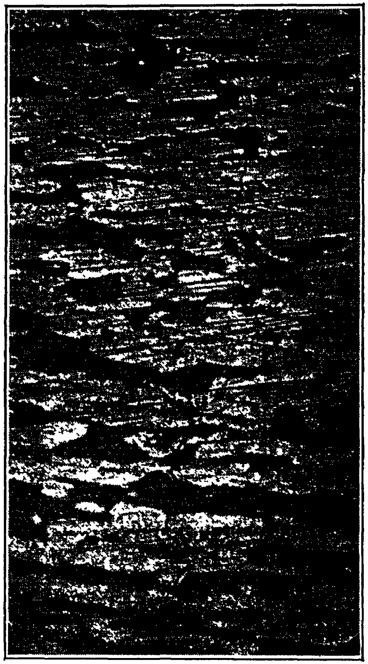


Figure 164. Fatigue Crack in Armco Iron

Original magnification 350 times—etched



(Courtesy of H. F. Moore)

Figure 165. Fatigue Crack in Brass

Original magnification 320 times—etched

in the case of ductile materials under static load. In the case of static loading in ductile material, any localized, excess stress would cause a flow of metal with an increase of resistance and a readjustment of stress with no danger of failure. If the material is brittle this readjustment is very limited. In the case of repeated stress, readjustment at the overstrained location throughout the stress range by means of plastic flow, whether the metal be ductile or not, is impossible to any great extent and sudden failure from fatigue may occur before the danger can be detected.

Experiments to Determine Endurance Limit.—Experiments to determine the endurance limit may be made on various types of testing machines. Most of the testing machines are made to test by means of repeated bending or torsion. In some, the stress remains always in the same direction; in some it is reversed. Samples are tested and the magnitude of the applied stress and number of repetitions to fracture are recorded.

Figure 166 is typical of the type of curve which would result from the plot of such tests.

In 1870, Wöhler published the results of a set of experiments, the important conclusions of which are stated by Kommers as follows:

"1. Wrought iron and steel will rupture at a unit stress much below the ultimate strength, and even below the elastic limit, if repeated a sufficient number of times.

"2. Within certain limits, the range of unit stress, not the maximum stress, determines the number of repetitions for rupture.

"3. As the range is diminished, for a given maximum or minimum unit stress, the repetitions for rupture increase.

"4. For a given maximum or minimum unit stress there appears to be a limiting range for which repetitions for rupture become infinite.

"5. As the maximum unit stress increases the limiting range of stress diminishes."

Goodman's Diagram.—A much better understanding of the influence of the range of stress upon the endurance limit will result from a study of what is commonly known as Goodman's diagram. Here the minimum values of the limiting ranges of stress are plotted as percentages of the static ultimate strength. (See Figure 167.) The maximum values of the limiting range are indicated by another straight line which is found to pass through the 50% static ultimate level when the minimum stress value is zero. When the positions of the lines of the diagram indicate equal positive and negative values, the limiting stress is 33% of the ultimate.

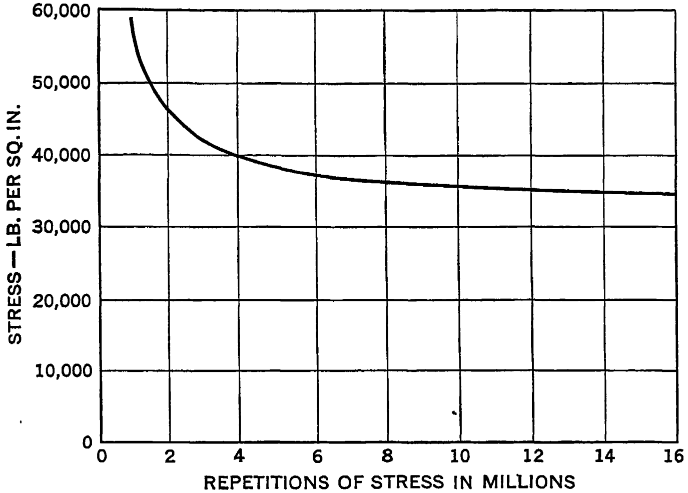


Figure 166. Typical Diagram for Endurance Limit of a Medium Steel

Examination of the diagram shows clearly:

1. That as the minimum stress approaches the static ultimate the range of stress approaches zero.
2. That for ordinary repeated stress the range is 50% of the static ultimate.

3. That for reversed stress the range is 66% of the static ultimate, since both the positive and negative values are 33%.
4. That the maximum stress which may exist without producing failure may be raised, provided the minimum stress is also raised enough to decrease the range of stress.

The above concepts are very important where difficult design involving such conditions is met.

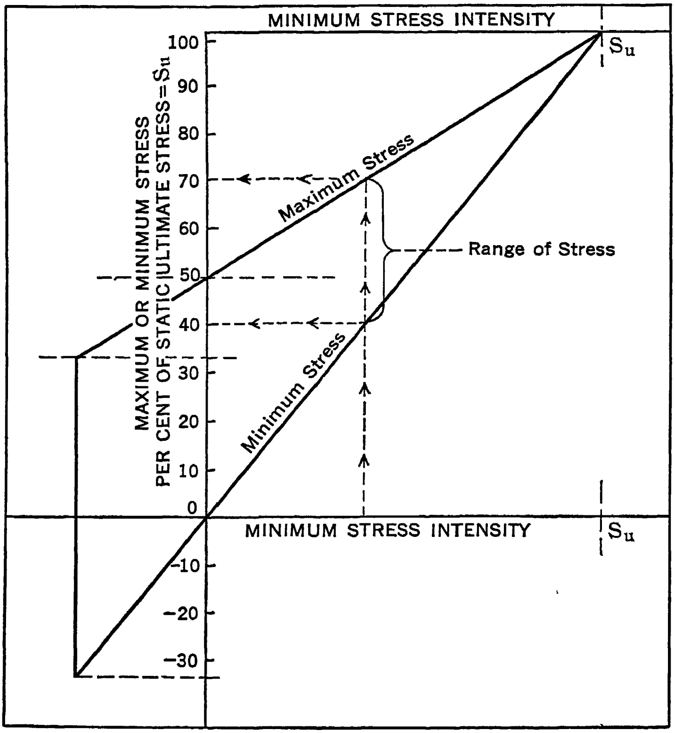


Figure 167. Goodman's Diagram of Range of Stress

Goodman's diagram has been criticized as being approximate, but Moore and Kommers show that it is on the side of safety, except in a very few reported cases, and the author concludes from their remarks that circumstances involving conditions of these tests and the reports thereon do not warrant the conclusion that the diagram indicates values which are too high. Results of experiments based on minimum stresses given show maximum values consistently above the maximum stress line; and while these do not lie quite on a straight line, the diagram is certainly sufficiently accurate for engineering design.

Effect of Heat Treatment on Endurance Limit.—While it is generally conceded that "previous history" has a great deal to do with the behavior of steels under repeated stress, it is quite apparent that heat treatment produces pronounced effects. Annealing seems to decrease endurance. Steel in the sorbitic state seems to be much more resistant, while in at least one case which has been reported from the Illinois investigations, steel in the troostitic condition was most resistant, showing an increase of 221% over the annealed material.

Effect of Speed.—Very low speeds of repetition of stress seem to decrease the endurance limit slightly while very high speeds raise it somewhat. In other words, the conclusion seems to be that the endurance limit increases somewhat as the speed increases.

Effect of Cold Working.—Examination of available data seems to lead to the conclusion that light cold working may possibly raise the endurance limit, but heavy cold working tends to set up severe internal stresses and strains, leading to the formation of minute cracks from which fatigue failure is apt to progress.

Effect of Case Carburizing.—Case carburizing has been found effective in raising the fatigue limit, particularly in bending and torsion which are conditions of non-uniform stress. The most effective results were obtained, according to examination of data published by Moore and Jasper, after a refining and toughening heat treatment of the case.

Effect of Chemical Composition.—Results of tests seem to show that for normal steels the endurance limit increases with the carbon content up to about 0.90% carbon, i.e., a little above the eutectoid composition. It is believed that the alloy steels are superior to carbon steels, but very little systematic study has been made, and conclusions cannot be drawn from fragmentary data.

Fatigue of Non-Ferrous Metals.—The general behavior of non-ferrous metals seems to be similar to that of steels, but in the case of some of the tougher alloys a great many more cycles of stress are necessary to develop the endurance limit than is the case in steel. In most cases 10,000,000 cycles is sufficient in steels, while some of the non-ferrous alloys require as many as 500,000,000 cycles.

Another point of difference is that for non-ferrous alloys the ratio of endurance limit to static ultimate stress is lower than is generally the case for the ferrous alloys.

Fatigue of Wood.—Although most of the experiments have been carried on on metals, some work has been done on fatigue testing of wood.

The data seem to indicate that when the applied unit stress is about ⅓ the static modulus of rupture or a little larger, failure may be expected to progress quite rapidly. The endurance limit is probably not far from 25% of the modulus of rupture, according to Moore and Kommers.

Fatigue of Cement and Concrete.—The expanding uses of concrete are making it necessary to use considerable care in design and study of conditions of loading. Many bridges and other structures are subject to repeated stresses of considerable magnitude.

Fatigue testing of concrete is fraught with considerable difficulty, but some work has been done. Enough has been discovered so that the conclusion has been drawn that concrete under repeated stresses behaves very much like steel under the same conditions of stress.

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CHAPTER 12

VARNISHES AND PAINTS

Varnish.—According to Sabin, varnish is a term commonly used to indicate a material which is applied to a surface as a liquid, and on exposure to the air hardens and forms a thin and usually transparent film (some varnishes are black and nearly opaque) which improves, or better displays the surface over which it is spread, and to a considerable degree protects it from dirt and injury.

Some varnishes harden by chemical change consisting in almost all cases of absorption of oxygen from the air. Other varnishes such as spirit varnishes and pyroxylin varnishes harden by evaporation of the solvent.

Ordinary Oil Varnishes.—These are made from certain resins, called varnish resins or varnish "gums" and *linseed oil* generally thinned with spirits of turpentine. *Long oil varnishes* contain much oil and less resin. *Short oil varnishes* contain more resin and less oil.

A word about varnishes may serve to warn the uninitiated against unwise selection for specific purposes. Simply because all varnishes look much alike, most people suppose that they are alike, and that any varnish put on in any way will do for any job. This is no more so than is the case with cloth. A thin silk would hardly be appropriate for a heavy winter overcoat, or a thin chiffon for a suit of overalls.

Varnish companies make scores of different varnishes and each kind is for some special purpose. Prices range from $1 or $2 per gallon to $6 or $9 per gallon, but the most expensive would not be as good for certain kinds of work as those which are less costly. The best varnishes must be made of the best oil and gum, and there can be no substitution of inferior and coarse ingredients.

Only the very best materials and most carefully controlled processes can produce a varnish that is hard and tough at the same time. Inferior hard varnishes are apt to be brittle, and conversely, tough varnishes are apt to be soft and sticky.

Quick drying varnishes are practically sure to be less durable than the slow drying type, for the driers always produce this effect when used in excess.

Varnish, hard as ice, which has no elasticity and which cracks easily, is easy to polish but is not durable and may be made from cheap materials.

Elastic varnishes which do not become tacky, and which may be rubbed if desired are only made from the best of materials with the greatest refinement of process. Low price varnishes that are full bodied are hard to apply and produce a poor finish. Low price varnishes that are thin and watery have little gum and require extra coats to produce a decent surface. There is no ultimate economy in inferior materials.

Spirit Varnishes.—Spirit varnishes are made by dissolving the resin in a volatile liquid such as alcohol. When the solvent dries, the resin is left spread as a uniform film over the surface.

Pyroxylin Varnishes.—These varnishes are often called lacquers. They are made by dissolving nitro-cellulose, or less often tetra-acetate of cellulose, in a very volatile solvent such as amylacetate or more recently butanol or cellosolve and methyl cellosolve. These solvents evaporate very rapidly on exposure to the air leaving an extremely durable film of pyroxylin which is similar to celluloid.

Linoxyn.—When linseed oil is spread into a film and exposed to the air it absorbs oxygen and becomes entirely changed into a tough, leathery substance completely different from the original oil. This new substance is called *linoxyn*, and it is the capacity for this change which causes linseed oil to be chosen for making paint and varnish. Although ordinary varnish generally has resin incorporated with the oil, the linoxyn itself is a sort of varnish and is sometimes used alone.

Varnish Vehicles.—Although linseed oil is the standard oil vehicle used in paint manufacture and undoubtedly the best, there are several others which are sometimes used for special purposes.

Soya bean oil, prepared from any one of several varieties of soya bean, has served as a substitute but is unreliable and tends to dry slowly.

Fish oil, particularly that from the menhaden, is sometimes used in conjunction with linseed oil. It has an objectionable odor and is very slow drying.

Perilla oil has high drying qualities but is not considered as a satisfactory substitute.

Tung oil, or China Wood oil, has rapid drying characteristics; is very repellent to water and when used with rosin will produce a hard, non-viscous surface in contrast to the sticky, viscous surface produced if rosin is used in ordinary oleoresinous varnishes. Tung oil varnishes, however, do not dry clear but rather flat or opaque.

Paint.—Paint is usually understood to be a material which contains a coloring pigment, suspended (not dissolved) in a liquid (called the vehicle) which, upon drying, produces an opaque film adherent to the surface to which it was applied.

Ordinary oil paint is made by mixing pigment with linseed oil, with the addition of some spirits of turpentine and drier.

Enamel paints are made by the addition of pigment to varnish.

Pyroxylin paints or colored lacquers are made by the addition of pigment to an ordinary pyroxylin varnish. The modern automobile body finishing material, of which "Duco" is a good example, is such a material.

Water paints. Water may even be used as a vehicle and when a dilute solution of glue is used with the pigment a paint commonly called kalsomine is produced. Such a mixture is also used in making water color or "distemper" painting. Water colors are often sprayed with ordinary varnish to enhance their beauty and make them more permanent.

Encaustic painting formerly was used to a considerable extent. It was done by mixing wax with suitable pigments and applying while hot. It was very durable when not exposed to heat or weather. This method should not be confused with that which uses wax in solution, such as is now used for floors, for encaustic painting was done with undissolved wax in the melted condition.

Thinners.—Thinners are used to change the viscosity of the oil vehicle and increase the capacity for spreading. Thinners also increase the penetration of the vehicle and therefore are used in "priming" or first coats to make the film grip the surface. Thinners also tend to produce a "flat" or non-gloss surface to which a second coat may be applied when the film is dry. Thinners dry mainly by evaporation and so do not enter into the composition of the film.

Turpentine is the standard thinner. It is particularly valuable because of its high solvent power, as well as for its ideal rate of evaporation. Benzol, gasolene, and naphtha are sometimes used as substitutes, but they are only satisfactory in a few special products.

Driers.—Ordinary oil driers are made by boiling lead and manganese in linseed oil to make a concentrated solution which is afterward added to raw linseed oil to produce what is called "boiled oil."

Japan driers are also lead and manganese compounds but generally largely dissolved in turpentine with some oil, and some resin.

Paints and varnishes as manufactured generally contain enough "drier" to promote a reasonable rate of drying. The driers usually sold in paint stores are oil soluble compounds of lead and manganese thinned with turpentine or some substitute. Five to 10% of these "Japan" driers will make a hard oil film in about 24 hours.

Use of Driers.—The general use of driers to produce very rapid drying is to be discouraged. Any drier is deleterious to the film because it tends to promote oxidation to the point where the film loses its toughness and the paint appears "burned." Paint experts use only enough drier to give reasonably rapid drying with the least possible injury to the film.

Pigments.—The ground minerals which are used as coloring materials in paint are added to the vehicle in the form of a very fine powder. The finer the grinding, the higher grade the pigment. In general the particles should be so fine that they will pass through a sieve having 200 meshes per linear inch.

Pigments not only color the vehicle but they stiffen it; that is, they produce a sort of mud, so that it is possible to spread a thicker film than would be possible without the pigment. Further than that, although linseed oil will dry to a hard film itself it is apt to be somewhat porous, while in the case of paint the pigment tends to fill the pores in the oil film and make a better protective coating.

Therefore the effects of the pigment are three fold: *first,* they produce the desired color; *second,* they make the film thicker and therefore a better protection; and *third,* they make the film less porous and therefore doubly improve the protective quality.

White Pigments.—*Basic carbonate white lead* is the most important white pigment. It is made by several different processes which produce slightly different characteristics but only an expert would have any preference. Basic carbonate white lead is the only pigment which is used extensively with oil alone. It is very durable and has great opacity. It weathers by flaking off finely and evenly, thereby making an ideal surface for repainting.

Basic lead sulphate is often used as a white pigment in combination with basic carbonate white lead or with zinc oxide, and as such is a valuable pigment. It seems to stand the attack of hydrogen sulphide better than the carbonate, and it produces a hard, non-porous film. It is often used in marine paints because of its resistance to the action of sea water.

White zinc or *zinc oxide* is produced by several processes. The best French process zinc white is very white, somewhat more so than basic carbonate white lead. It dries when mixed with linseed oil to produce a hard, glossy, impervious film, but it is apt to peel and does not lend itself to repainting. For this reason it is always used in paints with some other pigments and extenders. Addition of basic carbonate white lead prevents peeling and produces a better surface for repainting, although the gloss imparted by the zinc is still retained as well as the water repellent property.

Lithopone is a white pigment consisting of a chemical combination of zinc sulphide and barium sulphate. It is unusually opaque but not stable in the sunlight. Practically all of it is used in making interior flat finish for plastered walls. It is generally mixed with a rosin varnish the oil of which is tung oil thinned with turpentine. This dries very rapidly.

Auxiliary Pigments or Extenders.—These pigments are used to give body to a paint but in themselves are nearly transparent when ground in oil, but they affect the ratio of total pigment to oil in paint and are therefore used to correct this relation when other pigments are used.

Barytes is barium sulphate; it is a white, crystalline, heavy mineral, and is the most important auxiliary paint pigment. It is remarkable for requiring less oil to make a paste than any other pigment.

Asbestine is next in importance to barytes, but quite the opposite in regard to the oil requirements necessary to make a paste, since it takes a great deal of oil as compared with barytes.

It happens that white zinc and white lead differ from each other in the same way as barytes and asbestine and for some of the best paints the two are used together and one counteracts the effects of the other.

However, where no white lead is to be used, barytes is the natural extender to be used with white zinc and, on the other hand, where white lead but no zinc is to be used, the asbestine would be the better material. Asbestine is better than China clay, which it has nearly displaced on account of its non-settling qualities.

Powdered gypsum is sometimes used with delicate colors as it dulls them less than any other extender, but it is not extensively used. It is known in the trade as "terra alba."

Whiting, which is powdered chalk, is the finest, and softest, and least transparent of all the auxiliary pigments, and most all ready-mixed paints contain some of it.

Advantage of White Undercoat.—White undercoats for base for overlaying colored coats have been recognized as of value from great antiquity. References from some of the old masters are numerous enough to show that they fully appreciated the beneficial effect.

The effect of the white underbody upon a semi-transparent coat laid over it is to produce a tone of great warmth and splendor, while a dark undercoat produces a cold, lack-luster effect. It is supposed that the internal light produced by the reflection from the white undercoat is responsible for this effect. It is well worth the trouble of an extra coat.

Yellow Pigments.—The most important yellows are the chrome yellows, varying from light to dark with the degree of purity. They are somewhat inclined to fade on exposure but are fine colors and very opaque. Yellow ochres are not as pure in color but they are permanent and are used much in mixtures. Cadmium yellow is brilliant and permanent, but it is expensive. It is an excellent pigment.

Green Pigments.—*Chrome green* is the most important green. It is a mixture of chrome yellow and Prussian blue. The various chrome yellows produce different shades of green but all are of great opacity.

Paris green is aceto-arsenite of copper and is considerably used in inferior paints. Its color is unequalled, but it is a poor ingredient for paint.

Chrome oxide green is a true green pigment rather than a mixture like the chrome green noted above. Chrome oxide green is very permanent, indestructible, and opaque, but it is dull in color. It is quite expensive but is a valuable pigment and considerably liked.

Zinc green or *cobalt green,* which are different terms for the same pigment, is a compound of zinc and cobalt. It is a very permanent color of fine tone but is very expensive.

Blue Pigments.—*Prussian blue* or Chinese blue is a chemically prepared ferrocyanide of iron. It is dark but not an extremely good pigment, for it is not very opaque nor extremely permanent.

Ultramarine, which was originally made from the mineral lapis lazuli but which is now made artificially in great quantity, is the most important blue pigment. It is not very deep in color but is moderately permanent. It differs from most other pigments in that it is not improved by fine grinding.

Cobalt blue is a compound of cobalt and alumina. It is too expensive for ordinary paints but it is such a fine color and of such great permanence that it is largely used as an artists' color.

Red Pigments.—*Vermilion* is an artificial sulphide of mercury, of a beautiful scarlet color. It is not very permanent and is of rather high price, but has always been in considerable demand. It is known in this country as English vermilion since most of it is imported from England. That which comes from China is said to be of inferior grade.

American vermilion is a precipitate of a red coal tar color on red lead, orange lead or barytes, or even on sulphate or carbonate of lead. Real American vermilion is a good pigment of good color and very permanent, but there are other coal tar reds which are not fast colors and of inferior grade.

The basic red chromate of lead is called American vermilion by some but a more common name is *Persian red.*

Iron oxides are often used in cheap paints for wooden surfaces such as freight cars, barns, etc. They are quite variable in color and although dull, most of them are quite permanent, especially when pure. Indian red and Tuscan red are two of the best known of these oxide pigments.

True *red lead* is lead oxide, Pb_3O_4. Commercial red lead, however, contains considerable amounts of lead monoxide, a yellow pigment called litharge. Too much litharge is a bad thing because it reacts with the linseed oil and produces a thick lead soap called "liver." Red lead should be freshly mixed just before using. If 98% pure red lead is used it may be mixed as a linseed oil paste without danger of hardening in the can.

Red lead paint is used mainly on structural steel and metal work to prevent corrosion. It produces a hard and impervious film. It is difficult to apply because of its weight. There is always a tendency to add too much oil which destroys the protective qualities. The lowest limit of red lead to the gallon is 25 lb. and 33 lb. is preferable. Sometimes a filler such as silica or lamp black is used to produce a more uniform coating. Red lead is attacked and whitened by the carbon dioxide of the atmosphere and hence its use is limited to priming coats.

Black Pigments.—Black pigments are various forms of carbon. The ordinary varieties are bone black or ivory black, lamp black and graphite.

Bone black is made by calcining bone chips without the access of air; ivory black is made in the same way from ivory chips. Lamp black is made by burning oil or other hydrocarbon in an insufficient supply of oxygen. Bone black appears of a somewhat brownish hue in comparison with lamp black; but the better grades are specially treated to reduce this defect. Bone and ivory blacks of the better grades produce a very rich and velvety appearance.

Lamp black is a very fine and very light pigment. It retards the set of linseed oil, but makes one of the most permanent of paints.

House Painting.—The most common pigment used in this country for house painting, outside, is white lead or a white lead mixed with white zinc. These pigments are used either pure or extended with barytes, asbestine, silica, or other inferior materials.

The best authorities seem to agree that the mixed pigment paints containing both lead and zinc are the best for outside work, especially when proportioned and ground by reliable paint manufacturers. Linseed oil is the best oil vehicle to be had.

Priming coats should contain an excess of oil (some recommend pure linseed oil) and some turpentine. Final coats should contain more pigment and practically no turpentine. Several thin coats, each properly dried, are far better than a few thick coats. Driers should be used sparingly. Any drier is deleterious, but some is generally necessary. A good oil or varnish drier, Japan, is best, but a cheap rosin drier is very harmful and should never be used.

Where dark colors are desired there are other pigments which give excellent results: ochres, umber, sienna, and iron oxide are all good pigments, and, if lamp black can be used in appreciable amount, it imparts great durability.

Where a resinous wood like pine is to be painted and knots occur, difficulty is generally encountered by a staining of the paint over the knot locations. This is due to the resin in the wood which oil paint will not resist. These knots should be painted with a shellac varnish, upon which the pitch does not act, before painting.

Putty.—Ordinary putty is made of ground chalk, or whiting, to 100 lb. of which 18 lb. of raw linseed oil is added, and well mixed to form a plastic mass.

White lead putty contains only about ⅓ as much oil as common putty, and sometimes about 10% of it is mixed with common putty. White lead putty is sometimes used to fill cracks and for other special uses, but it becomes much too hard to use for setting window glass because of the difficulty of removing it in case it is necessary to reset the light. Marble dust which takes much less oil to make a paste is sometimes used as a substitute for whiting in making putty. It is utterly worthless and its use should not be tolerated.

Inside Painting.—Inside painting is generally considered much more complicated than outside painting, for fine appearance as well as permanence is essential. All wood should be thoroughly seasoned, and carefully sandpapered. For the best work it should be primed on the back with linseed oil before it is put in place. This is never agreeable to builders because it seems to interfere with their work, but for the best results it is essential. Unfortunately in ordinary construction it is rarely done. Finished outer surfaces should be carefully sanded and a coat of filler applied.

Fillers.—There are two sorts of fillers: liquid fillers and paste fillers. Liquid fillers commonly on the market are *rosin* compounds and should never be used for any purpose. If a liquid filler must be used, fill the wood completely with raw or boiled linseed oil or good varnish. There is no better filler than a good varnish. Unfortunately these are not ordinarily designated as fillers.

Paste fillers are really a kind of paint generally made of pulverized quartz and a quick drying varnish. They are spread thickly, rubbed in well with a brush and after standing a short time the excess is rubbed off with excelsior and then with felt.

When the interior, or exterior for that matter, finish is to be varnished, no filler should be used, the first coats of varnish furnishing the best filler that can be had. When these are used more coats are required, which is more expensive, but a fine and durable surface may be produced.

Enamel paints, that is pigment ground in varnish, are less opaque than ordinary paint and require an undercoat for best results. A good oil paint thinned with some turpentine is about the best undercoat which can be used. Special undercoat paints are made by reliable concerns which give a good underbody of maximum hiding power and sufficient durability. Cheap undercoats should be carefully guarded against, or peeling, flaking, or cracking of the film is sure to occur.

Paints for Structural Steel.—Red lead is undoubtedly regarded as the best material for the priming coat of structural steel. With linseed oil it produces a very tough, elastic film highly impervious to moisture. It does not weather well, however, and must be protected by a second coat of other oil paint or varnish paint.

Raw linseed oil alone is not a good protection, but the addition of some pigment or a little spar varnish is said to improve it greatly.

Bituminous paints are often used but are unsatisfactory, except when used in places not exposed to the sunlight.

Iron pipes are often protected by baking on a coat of linseed oil and subsequently dipping them in coal tar pitch mixed with linseed oil.

Metal surfaces should be thoroughly cleaned down to the bright metal. Paint will not stand long over any oxide deposit, and to paint over a rusted article of steel or iron is a waste of time and material.

There are many paints for many special purposes, but there is no such thing as an "all around" good paint or varnish. Special material is available for each purpose, and proper selection is essential.

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